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REMOTELY OPERATED VEHICLE ROV/AUV

RELIABILITY STUDY

PHASE II FINAL REPORT

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16. Abstract (Limit: 200 words)

A REMOTELY OPERATED VEHICLE (ROV) RELIABILITY STUDY WAS INITIATED IN TWO PHASES TO DETERMINE HOW ROVs CAN BE DESIGNED AND BUILT TO ACHIEVE ENHANCED OPERATIONAL RELIABILITY WHEN OPERATED DURING EXTENDED UNDERWATER DEPLOYMENT. THE CONTRACTOR WAS TO EXAMINE THE TECHNOLOGY USED IN THE DESIGN AND CONSTRUCTION OF REPRESENTATIVE ROVs WHICH ARE CURRENTLY STATE-OF-THE-ART AND DOCUMENT PROPOSED DESIGN OR CONSTRUCTION METHODOLOGY TO EFFECT HIGH RELIABILITY. THIS REPORT IS THE CONTRACT FINAL REPORT OF THE PHASE I STUDY EFFORTS AND PHASE II STATEMENT OF WORK (SOW) DEVELOPMENT.

THE RESULTS OF THE PHASE I STUDY WERE COMPILED AND DETAILED IN THE STUDY REPORT (DELIVERED SEPARATELY). IT WAS RECOMMENDED THAT EFFORTS SHOULD BE INITIATED UP FRONT TO DEVELOP TECHNOLOGICAL APPROACHES AND DESIGN AND MANUFACTURING CRITERIA TO ADDRESS THE LONG TERM RELIABILITY PROBLEMS IDENTIFIED IN THE STUDY. A PRIORITIZED LISTING OF RECOMMENDED THEORECTICAL AND EXPERIMENTAL WORK WAS DEVELOPED FROM THE STUDY RESULTS AND FORWARDED IN THE FORM OF A PROPOSAL FOR PHASE II TASKING APPROVAL.

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Report Documentation Page

THE PHASE II TASKING WAS APPROVED BY THE SPONSOR AND SOWs WERE DEVELOPED FOR THE TECHNICAL AREAS OF INTEREST.

THE RESULTS OF THE PHASE II SOW DEVELOPMENT ARE PROVIDED AS APPENDICES TO THIS REPORT. IT WAS INTENDED THAT THE SOWs DEVELOPED IN PHASE II WOULD BE USED TO GENERATE SOLUTIONS IN THE FORM OF RELIABILITY DESIGN SPECIFICATIONS, GUIDELINES AND DOCUMENTATION FOR THE PROBLEMS.

IN A FOLLOW-ON EFFORT, THE CONTRACTOR WILL PROVIDE EXPERT TECHNICAL PERSONNEL, MATERIALS, AND FACILITIES NECESSARY TO SUPPORT EXECUTION OF THE INDIVIDUAL CONTRACTS FOR THE SOWs.

TABLE OF CONTENTS

I. EXECUTIVE SUMMARY

A Remotely Operated Vehicle (ROV) reliability study was initiated in two phases to determine how ROVs can be designed and built to achieve enhanced operational reliability when operated during extended underwater deployment. The contractor was to examine the technology used in the design and construction of representative ROVs which are currently state-of-the-art (Phase I) and document proposed design or construction methodology to effect high reliability (Phase II). This report is the final report of the contract, focusing on the Phase II Statement of Work (SOW) development. The Phase I study report was delivered previously.

The Phase I study results revealed that the process of development and procurement of ROVs for Navy use presently involves modification of off-the-shelf commercial vehicles. Long term reliability is not a design criterion for commercial vehicles and is certainly lost in the development process due to cost competition. As a result, commercial-grade vehicles with broad applications are modified for specific requirements. These vehicles have reliability and other problems as described in detail in the Phase I study report.

Present state-of-the-art ROVs cannot be modified to meet the reliability requirements of extended deployment vehicles. Development of a highly reliable long term deployment vehicle requires the rigorous use of a thorough development process. Experts in the field recommend that simultaneously with vehicle development, efforts should be initiated up front to develop technological approaches and design and manufacturing criteria to address the long term reliability problems identified in the study.

The results of the Phase I study were compiled and detailed in the Phase I study report. A prioritized listing of recommended theoretical and experimental work to improve vehicle reliability was developed from the study results and forwarded in the form of a proposal for Phase II tasking approval.

The approved Phase II tasking resulted in the development of SOWs for each of the technical areas of interest. The SOWs are provided herein as Appendix A. Two lists were also generated, one of manufacturers known to produce quality underwater connectors and another of manufacturers known to produce quality syntactic foam. These lists were provided to the Government under separate cover.

This final report, specifically Sections IV and V, describes how the SOWs and lists were derived, and details the interaction with the experts during list development. The resultant SOWs are included as appendices to this report. (The Contract Data Requirements List (CDRL), form DD1423, and Figure (1) to the SOWs, Acoustic Noise Levels, will be provided by the Government). It was intended that the SOWs developed in Phase II would be executed via contracts to generate solutions in the form of reliability design and specification guidelines for each of the problems.

II. ACKNOWLEDGEMENTS

The contractor would like to acknowledge the assistance of the following people in identifying experts in various technical fields:

Mr. Theodore Austin
NUWES, Keyport, WA

Mr. Dennis Hurst
Honeywell Inc.

Dr. Colin Sandwith
Applied Physics Lab
University of Washington

Dr. Robert Spindel
Director, Applied Physics Lab
University of Washington

Dr. Robert Wernli
NOSC, San Diego, CA

Mr. Jeffrey Wilson,
Naval Civil Engineering Laboratory

A list of the many technical personnel contacted and who participated during the course of this contract are listed in Appendix B.

III. **INTRODUCTION**

1. Summary

A Remotely Operated Vehicle (ROV) reliability study was initiated in two phases to determine how ROVs can be designed and built to achieve enhanced operational reliability when operated following extended underwater deployment. The contractor was to examine the technology used in the design and construction of representative state-of-the-art ROVs and document proposed design or construction methodology to effect high reliability. The results of the contractor's Phase I study effort is documented in reference (a).

The result of the Phase I study was a prioritized listing of recommended theoretical and experimental work for Phase II tasking approval.

The Phase II approved tasking included the preparation of Statements of Work (SOWs) for each technology area of interest to the government. The purpose was to address each of these technology areas thoroughly and to define the problems for generation of SOWs. The SOWs would be used to develop design guidelines, specifications and documentation for the ROV design engineers. The technology areas requiring the generation of SOWs were:

1. Hydraulics
2. Seals
3. Suspect Manufacturing Processes
4. Variable Ballast
5. Buoyancy Materials
6. Tether Assemblies
7. Dry Connectors
8. Magnetically Coupled Thrusters

In addition to the generation of SOWs, two lists, one to identify Reliable Connector Manufacturers and the other to identify reliable Syntactic Foam Manufacturers was requested by the government. These lists were provided under separate cover.

The SOW development methodology is described in Section IV. The methodology used to generate the manufacturers list is described in Section V.

2. Program Overview

2.1 Description of Work

The program was a two-phased study contract to determine how Remotely Operated Vehicles (ROVs) can be designed or built to achieve reliability of 0.98 or better when

operated during extended underwater deployment. The contractor was to examine the technology used in the design and construction of representative ROVs which are currently state-of-the-art (e.g. the Perry Offshore Systems' TRITON or AMETEK's SCORPIO) and document proposed design or construction methodology to effect high system reliability. The ROV system includes the launch, recovery and storage system, power and control cables and the tether storage and management subsystem that would be required to support the ROV when installed on platforms from which the ROV would be deployed.

2.2 Program Description

The contract for the study consisted of two phases: the first to review the design, manufacturing processes, materials used, sensors, lights, cables, connectors, handling systems and electronic component reliability of ROV systems; and the second, to develop, recommend and document specific design and manufacturing methodologies to use, or to change current practice as necessary to achieve the desired reliability. To satisfactorily complete this work, the contractor used consultants who are experts in the various ROV components and subsystems. The deliverable from the contract was to be a comprehensive technical report detailing technological approaches and design and manufacturing criteria to design, construct, and operate an ROV system having the desired reliability.

2.3 Program Modification

During the conduct of the Phase I study it became apparent that development of detailed technological approaches and design and manufacturing criteria to design, construct, and operate an ROV system having the desired reliability was an inappropriate next step and an additional step was required in the development process. The additional effort required definition of the problems in sufficient detail so SOWs could be generated. The SOWs could then be awarded as contracts to have the detailed technical approaches developed, and design and manufacturing criteria generated. This additional step was approved and has required a follow-on Phase III to execute the SOWs generated in Phase II.

2.4 Deliverables

The contractor provided a written report at the end of Phase I which was accepted and approved by the government prior to proceeding to Phase II. This document serves as the final report required at the conclusion of Phase II efforts. A program plan was developed for each program phase (delivered separately). Oral and written progress

reports were made as necessary during the conduct of this contract. A detailed description of the methodology for conduct of Phase I was included in the Study Report, reference (a). The methodology for the conduct of Phase II and the deliverable SOWs are included in this, the Final Report.

3. Reliability Study Discussion

3.1 The state-of-the-art and maturity of the ROV market with regard to the US Navy, has led to the U.S. Navy's use of commercial grade broad application vehicles that have been modified for specific requirements. Long term reliability is not a design criterion and is certainly lost in cost competition. Vehicles are required to operate for hours, not weeks; these ROVs can be easily retrieved and repaired, if necessary. Extensive maintenance is performed between the short operational periods. Present state-of-the-art ROVs cannot be modified to meet the requirements for reliability of extended deployment vehicles. Instead, a vehicle will have to be developed to meet the stringent requirements for extended deployments.

3.2 To develop a highly reliable, long-term deployment vehicle requires the rigorous use of a thorough development process. This process should include requirements definition, prototype design and development though full scale engineering development, and the associated test programs to ensure that the product being developed will meet the system design requirements.

3.3 The Phase I study identified several reliability problem areas that needed to be addressed. A thorough assessment of those problems along with identification of solutions would ensure that the reliability problems would be adequately addressed in any vehicle development.

3.4 A synopsis of the reliability problems considered significant for a future long-term exposure system shows that solutions would affect both the design and the manufacturing processes.

All of these problems must be addressed in order to bring an ROV system to a state of high reliability. In a majority of cases, however, this design for increased reliability will be at the expense of ease of maintenance. In most design changes to increase reliability, Mean Time Between Failures (MTBF) figures and those for the Mean Time To Repair (MTTR) are related in that an increase in the time between failures will increase the time required to repair the system.

Both simplicity of design and operational requirements are closely related to reliability. The more complex the system becomes and the more varied its requirements, the more unreliable it will become.

In conclusion, of the reliability problems identified in the Phase I study, the government chose to pursue the detailed investigation and development of Statements of Work for seven of them. The purpose of this report is to detail how the problems were addressed and how the Statements of Work were developed (Section IV). The methodology for development of the two lists is also included (Section V). This report provides the vehicle for forwarding the approved Statements of Work. The Manufacturers lists were provided to the Government under separate cover.

IV. **STATEMENT OF WORK (SOW) DEVELOPMENT METHODOLOGY**

1. Approach

The following is a description of the process by which the Statements of Work were generated:

1.1 The individual task problems were defined as completely as possible using inputs from experts identified during the Phase I study. The expert data base list was expanded during Phase II after discussions and meetings with persons identified to us as the expert or experts in the technological area of interest. Using these experts, the individual task problems were further confirmed as problems for the high reliability ROV designer. This confirmation process resulted in only one of the original problems being reclassified as a non-problem (dry connector failure from vibration) by the experts. The decisions were supported by the technical review board.

Through a variety of meetings, telephone contacts and on-site visits, the contractor developed specific problem definitions as well as specific potential solutions to the problems. Visits to experts located across the nation were necessary to discuss the problems and potential solutions for development of the Statements of Work. Included were meetings with NOSC for discussions on all eight problem areas, Gianinni Institute for discussions on magnetically coupled thruster assemblies, Harbor Branch Foundation for discussions on connectors and variable ballast systems, University of Washington APL for discussions on all eight problem areas, NCEL for discussions on tethers and connectors, Woods Hole Oceanographic Institution for discussions on all eight problem areas, NUWES for discussions on all eight problem areas, Brantner Sea Con, Impulse, D.G. O'Brien, Envirocon, Burton, for discussions on connector reliability, Rochester Corporation concerning tethers and connectors, Coors Ceramics for discussions on alternatives to the use of syntactic foam, Cuming Corporation, W. R. Grace, and Flotation Technologies for discussions on limitations of syntactic foam.

1.2 The detailed task problems generated in Section 1.1 were used by the contractor in developing the individual SOWs. After internal review, each draft SOW was reviewed by the respective Technology Review Board (TRB) member(s). The TRB consisted of expert(s) considered the most knowledgeable in their field and available. Their expertise was used to guide the development of the final SOWs. It should be noted that significant effort was made to ensure that both the experts and the TRB

member(s) were thoroughly indoctrinated with regard to the requirements and objectives of the contract. As a result, we found our experts and TRB member(s) very supportive of the SOW development and the Navy's effort to address technology reliability problems up front, prior to vehicle design. We feel this enthusiasm is reflected in the quality of the efforts put forth by the experts and TRB member(s). The ROV technical experts and TRB members are identified in Appendices B and C, respectively.

1.3 The developed SOWs were forwarded to the government for internal review and comment. On receipt of the comments, the necessary changes were incorporated into the SOWs. The final SOWs are forwarded as Appendix A to this Final Report. The Contract Data Requirements List (CDRL) form DD1423, and Figure (1) to the SOWs will be provided by the Government.

Major comments from government reviewers included their desire to include AUVs in the effort and to modify the design depth guidelines to include 3,000 feet and 20,000 feet.

1.4 During development of the SOWs, pertinent comments, technical inputs and general information were acquired from the experts which had direct bearing and inputs on how the SOWs were structured. These comments, technical inputs and information are considered important and are provided here as insight into the development of the SOWs.

1.4.1 Hydraulics Statement of Work

In developing the Statement of Work to solve chronic hydraulic system problems, the approach was reasonably straightforward. Although the problems are classic and generic to many hydraulic systems existing today, the experts developing the problem definitions focused on highly specialized aspects of hydraulic systems. For this SOW, the technical review board had considerable input.

1.4.2 Seals Statement of Work

As in hydraulics, the seals SOW was reasonably straightforward; however, the seal problem is very broad and includes static, rotary, and sliding seals, each of which requires a separate definition/solution. The broad nature of this SOW required a variety of expert input in order to accomplish precise problem definition.

1.4.3 Suspect Manufacturing Processes Statement of Work

The structuring of this SOW was difficult and it soon became apparent that the contracting approach being utilized for execution of the other SOWs was inappropriate in this effort. The developer of the suspect manufacturing processes list had to be an uninterested third party able to interface with the manufacturers providing inputs. To accommodate this approach, an SOW was generated for implementation by Marine Imaging Systems. The planned approach is as follows:

Marine Imaging Systems would contact those major manufacturers who have provided work vehicles to the government, who have production facilities and who have experience with production runs of medium and large sized remotely operated vehicle systems. These contractors would be requested to compile a list of ROV reliability problems they or their users have experienced that have resulted from past or present manufacturing errors or faulty production design. Participation in the error identification effort would be encouraged by offering manufacturers the results of the effort.

Marine Imaging Systems would compile those lists of real and potential errors as supplied by the manufacturers and form a matrix of errors, causes and recommendations/solutions. The deliverable from Marine Imaging Systems would be an outline of manufacturing errors and production design faults that have caused reliability problems for ROV systems in the past.

The list would be cross-referenced so that the designer and/or manufacturer of high reliability vehicle systems will be able to draw from it to help in preventing similar problems in future manufacturing processes. In order to protect the participating manufacturers who are providing the information, MIS would organize the information not by manufacturer but rather by the major vehicle categories. The list would also be sanitized for the protection of the individual manufacturers. Emphasis would be placed on identifying errors rather than those who experience them.

1.4.4 Variable Ballast Statement of Work

During Phase I of the study, emphasis had been placed on 1500 psi ROVs for variable ballast systems. During Phase II when 3,000 and 20,000 foot systems were to be considered it was realized that each of these depths would require its own unique approach. It was

discovered during Phase II that most of the Variable Ballast systems in use today for the deeper applications were designed in the early 1970's and many of the parts are obsolete and no longer manufactured. This new problem was also taken into consideration in developing the Variable Ballast SOW.

1.4.5 Buoyancy Materials Statement of Work

During early phases of research on the Buoyancy Materials SOW there were indications that the problem described in Phase I may have become obsolete, however further investigations showed that there was really no usable specification for quality syntactic foam for government applications. Further, the specifications in existence were outdated and, today, higher performing foams are in use. It was realized that there is a need for both design recommendations as well as specifications for high reliability foams.

1.4.5.1. Additional Tasking (Functional Alternatives to Syntactic Foam)

The Syntactic Foam task, to develop a Statement of Work, requested that MIS present alternative efforts that are ongoing to design pressure hulls from materials that would not require the use of syntactic. Our investigations were only into the unclassified activities of R&D efforts. Although some aspects of work underway at Coors Ceramics in Golden, CO were corporately classified, we were able to judge the state of the technology from a conceptual standpoint.

Historically, syntactic foam used for flotation on underwater structures has exhibited reliability problems over the long term. In an effort to find a more suitable solution to underwater systems buoyancy, a number of avenues have been explored. The most promising to date has been the elimination of any requirement for buoyancy by designing the structural components of the underwater system from lightweight materials. Classically, materials with a low weight to displacement ratio (light weight) have had low strength, even when designed into structures in such a way as to maximize strength (interior or exterior rib stiffening, lamination, etc.). New materials, specifically ceramics and Filament Wound Epoxy (FWE) composites have undergone extensive R&D and testing in an effort to produce workable configurations for large diameter cylinders strong enough to survive high compression forces.

1.4.5.1.1 Composites

Although FWE technology is not immature, most past applications for it have been in the aerospace industry where high compressive forces on cylinders are not typically found. One of the first major steps in utilizing reinforced resins in a pressure hull on a commercial submarine was made by a British firm, Slingsby Engineering Ltd., by the construction of several manned submersibles including a 21 ton lockout boat (LR5), from glass filament wound cylinders. Since the main cylinder in manned submersibles is typically large diameter, and the interior is only partially filled with equipment, these systems require substantial ballast loads. The same is not expected to be true for unmanned vehicles where functional diameters will be far less with smaller electronics and equipment densities.

The major limitation to composite hulls appears to be their low resistance to abrasion and shock. Delamination of the materials, resulting in significant structural weakening, has been the major effect of shock.

More recent experiments in Filament Wound Epoxy (FWE) cylinders under hydrostatic pressure have shown wall failure beginning with delamination due to the exposure of cylinder wall ends to hydrostatic pressure as well. Although this problem may be solved with wall-end treatment or sophisticated "outside-seal" endcap designs, the manufacturing process is not as straightforward as with some other materials.

Of the two materials now being used for the high strength component in composite structures (graphite and glass), FWE using glass fibers appears to be stronger, albeit heavier, in formulation where approximately 70% fiber content is used. Although graphite fibers result in more costly manufacturing processes and are lighter, they may be preferable over glass in applications where maximum buoyancy is required.

Recent experimentation with hybrid composites constructed from both glass and graphite FWE appear to have very attractive weight to displacement ratios. However, further testing is required to determine the suitability of these hybrid composites in environments where abrasion and shock loading will be found.

1.4.5.1.2 Ceramics

For decades, ceramics cylinders constructed from Pyroceram^{tm}, alumina, zirconia and silicon carbide have historically been viewed with potential for use as pressure hulls, yielding high strength and a low weight to displacement ratio. However, even more than composites, these materials are susceptible to damage from shock. There are many different formulae for ceramic materials and ongoing experimentation may provide more shock resistant materials. Although the Japanese have been applying ceramics to underwater buoyancy spheres for over 15 years, the actual application of these materials as cylinders in the marine environment is relatively immature. Some of the technological limitations in ceramics involve control of tolerances when manufacturing large diameter cylinders, although ongoing R&D may provide solutions to this.

The major limitation to the ceramic designs for pressure hulls still appears to be shock. In pure compression, ceramic cylinders posses extremely high strength and even more so in a spherical configuration. However, the materials used to date have a limited capacity to withstand shock, failing most often by spalling, chipping or cracking.

1.4.5.1.3 Overview

There appears to be, at the present time, an industry capacity limit to both FWE and ceramic cylinders for use in large diameters applications. Further there appears to be technology limitations to both concepts but significant funding is urging further technological developments at a rapid pace.

These developments may provide hull structures that would eliminate the requirement for syntactic foam modules. Although the American oceanographic industry commonly uses cylindrical pressure hulls constructed from FWE materials, for the near term, it appears that pressure hulls of the diameter required for medium and large size unmanned vehicles will be constructed from metals such as titanium and aluminum. The weight to displacement of these materials will require the attachment of low density modules such as syntactic foam to increase the overall system buoyancy.

1.4.6 Tether Assemblies Statement of Work

A major factor in developing the SOW to solve chronic problems in ROV powered tether systems was the apparent dichotomy between the design performance of tethers

(and underwater cables) and the actual manufactured product performance in real-world applications. This required careful examination of historical performance of a variety of cable types under a variety of conditions in order to predict problem areas that may occur in future high reliability tethers.

1.4.7 Dry Connectors Statement of Work

Research into the problem of dry connector failure proved that there is not a problem and those companies that had reported these failures described in Phase I, had simply been using improper components and ignored available design guidelines. It was recommended that this effort be dropped and a SOW was not developed.

1.4.8 Magnetically Coupled Thrusters Statement of Work

In closely defining the problem of limited power applicability to magnetically coupled thruster assemblies, two related and important problems became very apparent. These are: (1) the high level acoustic signature of bearings in water contact and, (2) corrosion problems from exposing sensitive thruster components to the environment. These new problems may also be solved through the use of magnetics and, as a result, were included in the SOW for magnetically coupled thrusters.

V. LIST DEVELOPMENT METHODOLOGY

1.1 Overview

In developing the lists of ROV system component manufacturers (Underwater Connectors and Syntactic Foam) the approach for each differed greatly due to the nature of the product application. Because there is an extremely limited application for syntactic foam and there are a limited number of companies that produce the product, generating the list of recommended syntactic manufacturers was a comparatively straightforward process. In contrast, the sheer number of underwater connector types available to the design engineer and relatively large number of connector manufacturers made the generation of the reliable connector manufacturer a much more complex process. Also, since far more people have had considerable historical experience with underwater connectors many more experts had to be consulted. The analysis of connector manufacturers required a lengthy process of assuring that the proper people were contacted in order to properly analyze the connectors available.

1.2 Connector List

There are approximately ten major American underwater connector manufacturers who supply the major portion of a 20 million dollar worldwide annual market. Of these manufacturers most have a good knowledge of their product performance in the field under working conditions over time as a result of feedback from their customers. In order to determine what companies provide reliable products in service it was necessary to interview many experienced users of many different kinds and types of connectors. Even the most experienced program managers de-emphasize electrical connector problems, because the connector component is physically small, relatively simple in design, and often low cost in comparison to the equipment or vehicle on which it is used. Therefore, it is usually expected to perform well. When it does not, it often jeopardizes entire programs and can result in very expensive losses. As a result, users find it in their own interest to provide failure data to the manufacturer.

The Phase II work included interviewing numerous experts in the field of underwater connectors. These people included major underwater systems manufacturers, commercial and Government underwater equipment users and Government program managers. Each had extensive experience with underwater connectors of a variety of types and styles.

The interviewees were virtually unanimous in their opinions of the companies who manufactured quality connectors. Some experts agreed that there is no foolproof connector and of the two companies favored for reliability, many experts had qualifying statements relative to each.

In selecting the reliable components produced by the two manufacturers, we chose to go to the manufacturers themselves. It was determined that, although they may be biased, the manufacturer has the most complete knowledge and data on individual design reliability. Consequently, it was in the governments best interest for the manufacturer to supply this data.

During interviews and discussions with the two manufacturers, individual connector and/or connector types were identified as being the most reliable. The list of reliable connectors was generated specifically with the assistance of the two manufacturers.

A description of connector types and typical applications accompanies the reliable connector list which was delivered separately.

1.3 Syntactic Foam Manufacturers List

There are less than ten manufacturers who have consistently produced syntactic foam for the American commercial and government market. This market is considerably smaller than the connector market and some manufacturers produce foam from very small facilities, on and off, as demand for small amounts of the product arise.

In analyzing the producers of this product, we chose to concentrate on the manufacturers that consistently produced the product and have had a history of doing so.

Although there are manufactures of quality foam in the U.S. and England, as a result of our Phase II interviews, it appears that there is no manufacturer of syntactic foam that produces a high performance foam that does not exhibit water pickup, eventual degradation from stresses encountered in deployment, and that is also not formulated from potentially harmful constituents. The development of the SOW on syntactic foam was directed at the definition/design of such a high performance foam (Appendix (A)).

One of the difficulties uncovered in defining individual reliability problems with syntactic foam is that many of the experts in this field work in the foam manufacturing industry. It was necessary, therefore, to look to individual manufacturers for some of the expertise required in defining individual problem areas.

A list of major syntactic foam manufacturers was prepared and provided to the Government under separate cover.

VI. CONCLUSIONS/RECOMMENDATIONS

1. Conclusion

To provide credibility to the development of the Statements of Work (SOWs) in Phase II, extensive effort was expended to identify the experts in each of the technological areas. Their expertise was subsequently applied to define the problems, define the approaches for solving the problems and to develop the SOWs. The result was the generation of seven detailed SOWs which are available for execution to address high reliability technological problems prior to the design/development of high reliability Remotely Operated Vehicles by the government. The experts identified during Phase II are available for the next phase of the program to support execution of the SOWs. Their participation will increase the chances of the government receiving a quality product.

2. Recommendations

It is proposed that the SOWs developed in Phase II be executed to generate solutions in the form of reliability design specifications, guidelines and documentation to the problems.

It is recommended that the experts be utilized to provide knowledgeable personnel to support execution of the SOW contracts. A detailed proposal describing the recommended approach for the use of experts in the execution of the SOWs has been prepared and provided under separate cover.

APPENDIX A

STATEMENTS OF WORK (SOW)

1. Hydraulic Systems
2. Magnetically Coupled Thrusters
3. Suspect Manufacturing Processes
4. Buoyancy Materials
5. Sealing Systems
6. Tether Assemblies
7. Variable Ballast Systems

STATEMENT OF WORK

FOR

High Reliability Remotely Operated Vehicle (ROV)

and Autonomous Underwater Vehicle (AUV)

Hydraulic Systems

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TABLE OF CONTENTS

STATEMENT OF WORK

1. BACKGROUND AND INTRODUCTION

Future Navy requirements will involve protracted deployments of underwater Remotely Operated Vehicles (ROVs) and Autonomous Untethered Vehicles (AUVs). To date, the performance of such vehicles has been heavily dependent on the quality and quantity of the maintenance and support available during relatively limited deployments. An ROV design that is appropriate for industrial (e.g., petroleum industry) operations, with limited exposure and the expectation of much maintenance, as a tradeoff against higher initial cost, is inappropriate for military missions with little or no opportunity for upkeep. As a result, the common practice of modifying existing ROVs and ROV subsystems for long term, at-sea storage and/or operation without maintenance is not considered to be a long term solution for extended mission Navy operations.

The following operational capabilities and reliability goals need to be achieved for the Navy to meet its long term deployment ROV/AUV requirements. The vehicles must be designed and built to achieve an operational reliability of 98% or better when operating from submarines during protracted deployments (3-6 months wet or in a powered-down configuration for one to two months followed by several weeks of subsequent operations). The ROV/AUV system operational capabilities to be considered are as follows:

1. The operational depth design consideration is a maximum of 3,000 feet. Consideration shall also be given to systems that have a maximum depth capability of 6,000 feet.

2. TETHERS:

   A. The ROV system shall have a 4,000 ft powered tether working from a station keeping platform with a maximum distance from the platform of 3,000 feet in any direction. Station keeping is defined as zero relative velocity between platform and geodetic or geographic surroundings.

   B. The AUV shall have no tether.

3. The ROV or AUV system shall have low self-radiated noise, according to the goals shown in Figure I, and its auxiliary acoustic components shall not interfere with the platform sensors. The entire system should minimize acoustic radiation.

4. The ROV or AUV system's magnetics shall not interfere with the platform or its sensors and vice versa.

5. The ROV's capacity for a variety of work tasks, including heavy duty work and high power manipulators, shall also be considered.

6. The ROV's or AUV's maximum nominal speed shall be 5 knots.

All aspects of the system life cycle that may offset reliability were considered in an initial investigation, including; design, procurement practices, fabrication, inspection, in-service use and maintenance. The reliability problems identified in the investigation report covered the entire development phases of design, manufacturing and in-service life. The in-service life phase, concerned with training, maintenance and documentation are not to be considered under the tasking of this SOW, but later on as part of a specific system design. The focus of this SOW is on the application of technology to improve reliability.

Specifically, this statement of work addresses ROV/AUV hydraulic systems reliability problems and how their design might be improved to help obtain the long range Navy objective of achieving a substantial increase in the extended mission reliability of ROVs/AUVs.

2. APPLICABLE DOCUMENTS

2.1 Other Government Documents

The following Government document forms a part of this specification to the extent specified herein.

David Taylor Research Center, Annapolis - Ocean Engineering Handbooks

3. SCOPE

The objective of this SOW is to provide recommendations for specific solutions to chronic failures in hydraulic systems. This will be presented in the form of deliverables so that designers can use this information in the creation of new vehicles and systems, or in troubleshooting/retro-fitting existing systems.

The work will be focused on ways to improve the reliability of hydraulic systems, including associated controls, plumbing and fittings. The trend toward quieter vehicles, and therefore quieter and lower power hydraulics, is recognized as a major future design goal. Quieting a system works against reliability in a volume constrained system, and can, with a high reliability ROV/AUV, drive up the size

and complexity of the vehicle. Consequently, the contractor shall conduct design trade-offs to select the optimum hydraulics design affording the desired reliability level with the least noise.

Hydraulic failures (unrelated accidents excepted) can come about for a wide variety of reasons, but they may be grouped into two major areas of proximal cause:

* Those traceable to faulty design
* Those resulting from faulty materials or manufacturing processes.
* Those resulting from improper building, assembly or manufacturing workmanship.

The SOW is organized around the two areas of design and fabrication with "faulty materials or manufacturing processes" included under the latter area. Further, the SOW is structured so as to treat each thoroughly, with the failure modes as documented to date and described in detail in Section 4. The Design (4.1) and Manufacturing (4.2) subheadings deal with the breakdown of the two major categories into areas of specific interest.

4. REQUIREMENTS

The contractors proposal shall identify from an overview how to approach each problem technically, alternative approaches, costs and schedules. The approach shall address the two major reasons for hydraulic failures as delineated above in Section 3 and as follows.

The contractor shall examine common failure modes of vehicle hydraulics and recommend design and/or procedural solutions to these problems so that they can be implemented at a later date for testing and/or evaluation purposes. These solutions will be in the form of deliverables described later in this section of the SOW. The deliverables shall reflect the current state-of-the-art technology, and assume implementation in the next five years.

4.1 Critical Design Areas

The overall objective is reliable longer-term deployment of ROVs/AUVs than is possible with current commercial vehicle designs modified to meet Navy requirements. Several specific critical areas have been identified which must be addressed in order to improve reliability to an acceptable level. In dealing with specific design recommendations for maximizing system reliability, the contractor must keep in mind that these must be based on the realization that compromise is an inevitable part of every design effort. Consequently, the importance of each recommendation,

relative to other recommendations, must be indicated. Further, the contractor shall provide reasonable comparison information on the application of less than optimum alternatives and their possible consequences.

The contractor shall give consideration to the effect of noise reduction criteria on system design (see Figure I Goals) and resulting reliability to provide the designer with adequate information to properly evaluate the consequences of the trade- offs involved. As an example; (a) the relative merits of low pressure/high volume vs. high pressure/low volume systems, (b) output power vs. quieting, (c) volume occupied vs. quieting, and (c) output power to input power ratio vs. quieting shall be carefully documented.

4.1.1 Hydraulic System Leaking and Flooding Problems

The contractor's critical design review must consider leaking and flooding involving the loss of hydraulic fluid overboard and the ingress of water. The loss of fluid overboard is a problem because of the relatively long time between service/maintenance opportunities. The ingress of water presents corrosion, lubrication, and particle contamination problems.

Hydraulic fluid loss and water ingress in underwater hydraulic systems can come about through faulty or improperly installed line termination, fittings on motors/pumps/compensators, faulty hydraulic lines or corroded mechanical components. Another potential leak site is rotary seals on moving shafts in the hydraulic propulsion system. These seals commonly experience excessive friction and wear which can lead to failure of the seal integrity over a period of time. Most existing hydraulic systems can tolerate a limited amount of fluid loss or contamination because of the use of sufficient fluid quantities and filters in the system. This scenario is not acceptable for a system undergoing long deployments and this problem requires solutions to prevent both a loss of fluid and ingress of water into the system.

4.1.1.1 Manifolds

The use of manifolds machined from solid stock to mount and interconnect control valves and even some power devices such as linear actuators shall be examined. The objective is to minimize the quantity of potential leakage sites. This approach can reduce the quantity of potential leak sites (as well as the space required for lines and fittings) by a significant factor. It is realized that when manifolds vice smaller and more convenient

connections are employed there may be a serious trade off between the Mean Time To Repair (MTTR) figures and the Mean Time Between Failure (MTBF) figures. In designing systems to secure high reliability, it may make the vehicle harder to repair at a forward deployment site and require its return to the manufacturer for repair. This process is time consuming, very costly, and adversely affects the availability of the vehicle. It is desirable for these hydraulic systems to be configured in a manner that considers the trade-offs between repair in the field or at the factory. The contractor shall provide recommendations for the use and design of manifolds in the final report. The contractor shall also analyze the tradeoffs expected between MTBF and MTTR figures using manifold vice single connection interconnects and include these tradeoffs in the final report (CDRL item #A005).

4.1.1.2 Welded Lines

The contractor shall examine the use of welded piping assemblies and subassemblies to decrease the number of leak sites. Consideration shall be given to the weldability of the specific materials suitable for use in a high pressure, vibrational, long term salt water immersed application. It is acknowledged that the use of welded lines to increase system reliability carries the same advantage and disadvantage in terms of MTBF versus MTTR figures as the use of manifolds (section 4.1.1.1.). Considering that maintenance and repair is desirable at a forward deployment site in order to increase the systems' availability, the trade-offs between the use of welded lines and the use of other line fittings shall be evaluated. The contractor shall provide recommendations for and/or against the use of welded lines and suitable materials in the final report. The contractor shall also provide the analysis and tradeoffs in MTBF and MTTR figures when using welded lines vice line fittings in the final report (CDRL item #A005).

4.1.1.3 Threaded Connections

The need for some threaded connectors is recognized and the relative merits of the various types available shall be investigated. Since many system components are available with a limited number of interconnection fitting choices, evaluation of these choices shall be made to provide analysis of their suitability. For example, it may be shown that a single pipe fitting decreases system reliability by an amount equivalent to using 10 "O" seal fittings

but that seal welding the pipe fitting results in a joint equivalent to socket welding. The contractor shall compare and report on the suitability of these connections in the final report (CDRL item #A005).

Methods for correcting the deficiencies in existing threaded joint designs shall be considered in the hope that the specific low maintenance application will allow improvements. As an example, it may prove practical to utilize tack welding to overcome the tendency of a threaded connection to loosen in a high vibration environment. The contractor shall provide recommendations for improved design of threaded connections in the final report (CDRL item #A005).

The choice of acceptable materials for threaded connections shall be carefully evaluated. Particular attention shall be paid to problems of crevice corrosion and stress corrosion cracking in a salt water environment. Again, the low maintenance application may allow use of novel solutions such as joint encapsulization in a suitable conformal coating. The contractor shall evaluate and recommend acceptable materials for threaded connections in the final report (CRDL item #A005).

4.1.1.4 <u>Pressure Loaded Compensator Connection Seals</u>

Typically a hydraulic system that is designed for underwater operation is equipped with a pressure compensator that maintains hydraulic system pressure at or slightly above the ambient water pressure. When the hydraulic fluid pressure is slightly above water pressure, if a leak does occur, oil will leak out. This is usually the preferred situation to minimize the possibility of system degradation due to corrosion. Examination shall be made of optimum compensator connection points and pressures. Both active and passive methods for providing compensation pressure shall be evaluated. The examination results and recommendations shall be presented in the final report (CDRL item #A005)

4.1.1.5 <u>High Friction Seals</u>

At rotary and sliding seals special seal methods such as advanced lip or O-ring seal, redundant seal, or hermetic boundary seals shall be examined. The contractor shall examine the long term effect of both oil and water on these seals. Further, the contractor shall specify or design and qualify these high reliability sealing methods as a potential solution to leaking and flooding. The contractor

shall provide these specifications, designs and/or qualifications in the final report (CDRL item #A005). The contractor shall quantify seal leakage rates to expect after 1000 operational hours and associated passive exposure to saltwater and/or oil.

4.1.1.6 Other Potential Leak/Flood Problems

There are many different hydraulic component designs now in use on Remotely Operated Vehicles. Each of these systems may have unique problems with respect to the loss of fluid or ingress of water. The contractor shall detail any other problems of concern to a design engineer of which he may be aware and provide potential solutions for these problems in the final report (CDRL item #A005).

4.1.2 Hydraulic Line Failure Problems

Line failure can be caused by several system-design or operational problems. The major causes of line failure following acceptance testing are; corrosion, abuse, and fatigue resulting from pressure and large spikes or pulsations. Failure modes are normally bursting or leakage but other, less common, failure modes exist.

Any hydraulic line that carries fluid at or near ambient pressure is susceptible to possible collapse. The line will collapse if the internal pressure is sufficiently lower than the external pressure and line walls are of inadequate strength. Such a line is in unstable equilibrium. If constant flow is maintained, once collapse starts it will tend to quickly proceed to complete collapse. Lower internal pressure is due to two factors; low hydrostatic pressure at the exit end of the line, and fluid flow velocity (which reduces hydrostatic pressure at the line wall) within the line. Bends, external loads or rapid pressure changes due to pulsations can aggravate the situation. Collapse in a pump suction line can also occur if the system compensator bottoms (due to a leak somewhere in the system) and the pump continues to deliver fluid. Since hose generally is weaker than tubing or pipe, it is the more likely system element to fail by collapsing.

4.1.2.1 Contamination

Despite a competent manufacturing process, maximizing reliability will involve both particle and water removal. The contractor shall consider the various methods for accomplishing this and make recommendations; specifically the type, fineness, location, quantity, size, leakage potential and fail safe aspects of available filtering components shall

be addressed. The contractor shall also provide recommendations on cleanliness levels and associated procedures. The contractor shall provide these recommendations in the final report (CDRL item #A005).

4.1.2.2 Hydraulic Line Noise

The contractor shall review those areas of existing hydraulic system design practices, Navy and commercial sound silencing techniques, and the use of noise reduction components (i.e. flex hoses and sound dampeners) with the goal of achieving the desired reliability level and reduced acoustics radiation. The impact of these designs/components on reliability shall be examined and specific recommendations made. The contractor shall provide these recommendations in the final report (CDRL item #A005).

4.1.2.3 Working Fluids

Trade-offs between various working fluids in the system shall be considered for ROV/AUV deployments with particular attention to long term wet storage of the system and extended power down periods. Consideration shall also be given to whether periodic start-up/exercise of hydraulic systems is necessary or desirable. The contractor shall provide these trade-offs and make recommendations in the final report (CDRL item #A005).

4.1.2.4 Other Potential Line Failure Problems

Depending on the type and design of the hydraulic lines in any given system, there may be unique problems with line failure not covered in this section. The contractor shall detail any other problems of concern to a design engineer and potential solutions of which he may be aware. The contractor shall provide a description and discussion of these problems and potential solutions in the final report (CDRL item #A005).

4.2 Manufacturing

Even with reliable, quality designs for all parts of a vehicle, system errors in manufacturing involving the incoming materials or components from vendors, fabrication of materials in house and the assembly of these can cause a reduction in the overall system reliability. These errors can be product-wide and effect virtually all units in a production run and result in multiple in-service failures before detection.

4.2.1 Components

Incoming components for the production of vehicle systems are most often either tested by the manufacturer or certified as tested by the vendor. Even if the components are certified by the vendor they can still be faulty and cause unpredictable failures in service. In some vehicle systems, manufacturers will utilize marginally reliable components due to either cost competition or component availability.

4.2.1.1 Component Failure

The contractor shall review the available components used in the manufacturing of ROV/AUV systems with regard to their reliability history. The contractor shall consider whether the formulation of a Quality Parts List (QPL) for ROV/AUV systems will improve their reliability and make his recommendation in the final report (CDRL item #A005).

4.2.2 Fabrication and Assembly

Errors in fabrication and assembly which may be missed by even a good quality assurance program, may weaken the product and create later in- service failures. Identification and documentation of these known errors can contribute to their elimination.

4.2.2.1 Manufacturing Errors

During the contract it is expected that the contractor shall develop a list of common manufacturing errors found to cause various types of hydraulic failures. This list will be valuable in warning the vehicle designer or manufacturer of their existence. The contractor shall make this list available as an attachment to the final report. The list of errors shall include explanations, desirable alternative solutions, and recommendations (CDRL item #A004).

4.3 Reference Documentation

DTRC (Annapolis) has published a series of Ocean Engineering Handbooks on topics ranging from electric underwater motors to hydraulic systems. These handbooks provide the designer with examples, design data, standards and other information of great practical value during the design process. The contractor shall draw on these and other sources of information (as described elsewhere in this SOW), and on his own extensive experience in the design and implementation of underwater hydraulic systems of all types, and produce a

compendium of specific guidelines on how to design to prevent problems (historical and expected) which plague ROV hydraulics reliability. This compendium shall be presented as an attachment (CDRL item #A003) to the final report.

The contractor shall make a thorough survey of applicable military standards, specifications and handbooks. The contractor shall compile all such documents, cross-referenced and explained so that the designer will have a single, concise source for selection of applicable controlling documents to reference during the preparation of material, process, or product specifications. The contractor shall provide this compilation as an attachment (CDRL item #A003) to the final report.

5. DELIVERABLES

Designer Guidelines for the technical aspects of the hydraulic system which contribute to failures shall be a prime product (CDRL item #A005). The contractor shall produce a compendium of specific design guidelines for preventing problems which plague ROV hydraulics systems (CDRL item #A003). The contractor shall also provide a list of common manufacturing errors found to cause hydraulic failures (CDRL item A004). Other deliverables required are a program plan (CDRL item #A002), status reports (CDRL item #A001) and a final report (CDRL item #A005).

The deliverables on this project shall be in contractor format and in accordance with the attached Contract Data Requirements List (CDRL), Form DD1423. The details of the required deliverables are as follows:

5.1 Program Plan (A002)

The contractor shall develop a program plan in accordance with CDRL #A002 identifying: how to approach each problem technically (including breakpoints), alternative approaches, and a schedule for each required deliverable in section 4 of the SOW. The plan shall elaborate on the contractors proposed technical approach to the SOW and detail how the contractor will perform each required item within the allocated time and cost. A draft program plan shall be delivered 30 days after contract award, and is subject to Government approval. A final version of the program plan, with Government comments incorporated, shall be required 15 days after the contractors receipt of the Governments comments.

5.2 Project Status (A001)

The contractor shall provide project status in accordance with CDRL #A001 by the fifteenth of each month for the previous calendar month.

5.3 Final Report (A005)

A draft final report prepared in accordance with CDRL #A005, describing all research results and conclusions, shall be submitted 60 days prior to completion of the contract for review and comment.

A final report updating the draft report, as required by the review comments, shall be submitted 30 days after the contractors receipt of the Governments comments on the draft report.

Specific deliverables to be included in the final report are the following:

5.3.1 Problem Documentation (A005)

Section 4 requires the contractor to provide evaluations, designs, specifications, comparisons, trade-offs, descriptions, discussions and/or recommendations for each specific problem and to include the results as separate, identifiable items in the final report. The results shall be prepared in accordance with CDRL #A005 for the ROV/AUV hydraulics components, subsystems, supporting/auxiliary equipment or processes as directed in items 4.1 through 4.2 inclusive, less item 4.2.2.1 Manufacturing Errors. The specific items to be reported are:

(4.1.1.1) Manifolds

Recommendations for the use and design of manifolds. Provide an analysis of trade offs between MTBF and MTTR figures using manifolds vice singular interconnections.

(4.1.1.2) Welded Lines

Recommendations for the use of welded lines and suitable materials. Provide an analysis and the tradeoffs in MTBF and MTTR figures when using welded lines vice line fittings.

(4.1.1.3) Threaded Connections

Provide comparisons and applicability of threaded connections, and recommendations for improved design of threaded connections. Provide an evaluation and recommendations of acceptable materials for threaded connections.

(4.1.1.4) Pressure Loaded Compensator Connection Seals

Provide recommendations of optimum compensator connection points and pressures (active and passive) for seals.

(4.1.1.5) High Friction Seals

Provide specifications, designs and/or qualifications for sealing methods. Provide a quantification of seal leakage rates expected after 1,000 hours of operation with high friction seals.

(4.1.1.6) Other Potential Leak/Flood Problems

Provide a description, discussion and potential solution for each problem identified.

(4.1.2.1) Contamination

Recommendations for removal of particle and water contamination during the manufacturing process and recommendations on cleanliness levels and associated procedures.

(4.1.2.2) Hydraulic Line Noise

Recommendations for the use of designs/components on noise reduction and reliability.

(4.1.2.3) Working Fluids

Provide trade-offs between various working fluids and make recommendations. Include recommendations on the desirability/necessity of periodic start-up/exercise of hydraulic systems.

(4.1.2.4) Other Potential Line Failure Problems

Provide a description, discussion and potential solution for each problem identified.

(4.2.1.1) Components

Provide an assessment and recommendations of a Quality Parts List (QPL) program for ROV/AUV systems.

5.3.2 Reference Documentation (A003)

The contractor shall provide a compendium of specific guidelines on how to design to prevent problems which plague ROV/AUV hydraulics reliability.

The contractor shall make a thorough survey of applicable military standards, specifications and handbooks. He shall compile all such documents, cross-referenced and explained so that the designer will have a single, concise source for selection of applicable controlling documents to reference during the preparation of material, process, or product specifications. (Item 4.3 Reference Documentation.)

5.3.3 Manufacturing Errors (A004)

The contractor shall provide a list of common ROV/AUV hydraulics manufacturing errors including desirable alternative solutions and explanations. (Item 4.2.2.1 Manufacturing Errors).

STATEMENT OF WORK

FOR

High Reliability Remotely Operated Vehicle (ROV)

and Autonomous Underwater Vehicle (AUV)

Magnetically Coupled Thrusters

Prepared By:

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Prepared For:

Office of Naval Research (ONR)
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(ONR Code 122)

TABLE OF CONTENTS

STATEMENT OF WORK

1. BACKGROUND AND INTRODUCTION

Future Navy requirements will involve protracted deployments of underwater Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs)the performance of such vehicles has been heavily dependent on the quality and quantity of the maintenance and support available during relatively limited deployments. An ROV design that is appropriate for industrial (e.g., petroleum industry) operations, with limited exposure and the expectation of much maintenance, as a tradeoff against higher initial cost, is inappropriate for military missions with little or no opportunity for upkeep. As a result, the common practice of modifying existing ROVs and ROV subsystems for use in military service is undesirable and is not considered to be a long term solution for extended mission Navy operations.

The following operational capabilities and reliability goals need to be achieved for the Navy to meet its long term deployment ROV/AUV requirements. The vehicles must be designed and built to achieve an operational reliability of 98% or better when operating during protracted deployments (3-6 months wet or in a powered-down configuration for one or two months followed by several weeks of subsequent operations). The ROV system operational capabilities to be considered are as follows:

1. The operational design depth consideration are maximums of 6,000 feet and 20,000 feet.

2. TETHERS:

   A. The ROV system shall have a 4,000 ft powered tether working from a station keeping platform with a maximum distance from the platform of 3,000 feet in any direction. Station keeping is defined as zero relative velocity between platform and geodetic or geographic surroundings.

   B. The AUV shall have no tether.

3. The ROV or AUV system's shall have low self-radiated noise, according to the goals shown in Figure I, and its auxiliary acoustic components shall not interfere with the platform sensors. The entire system should minimize acoustic radiation.

4. The ROV or AUV system's magnetics shall not interfere with the platform or its sensors and vice versa.

5. The ROV's capacity for a variety of work tasks, including heavy duty work and high power manipulators, shall also be considered.

6. The ROV's or AUV's maximum nominal speed shall be 5 knots.

All aspects of the system life cycle that may offset reliability were considered in an initial investigation, including; design, procurement practices, fabrication, inspection, in-service use and maintenance. The reliability problems identified in the investigation report covered the entire development phases of design, manufacturing and in-service life. The in-service life phase, concerned with training, maintenance and documentation are not to be considered under the tasking of this SOW, but later on as part of a specific system design. The focus of this SOW is on the application of technology to improve reliability.

Specifically, this statement of work addresses ROV/AUV magnetically coupled thruster assemblies and how to improve their power and reliability without undue increase in size or complexity. The objective is to improve the design of magnetically coupled thrusters to help achieve a substantial increase in the extended mission reliability of Navy ROVs/AUVs.

In current state-of-the-art ROV systems there are a number of different propulsion system designs. One of the more reliable designs utilizes an air backed electric motor. Although the average life of this type of thruster design is comparatively long, one of the components of this assembly with the shortest life cycle, is a rotating shaft seal where the propeller shaft penetrates the pressure housing containing the motor. In many designs this seal, although reliable in the short term, demonstrates extremely high wear rates and requires frequent maintenance.

One type of thruster design implemented on a number of ROVs eliminates these shaft seals altogether through the use of magnetic fields which transfer rotational power without the use of sealed, pressure-housing-penetrating shafts. By eliminating shaft seals altogether the reliability of the electric thruster has been greatly improved allowing long term deployments with little or no maintenance to the thruster assemblies.

2. APPLICABLE DOCUMENTS

2.1 Other Government Documents

The following Government document forms a part of this specification to the extent specified herein.

David Taylor Research Center, Annapolis - Ocean Engineering Handbooks

3. SCOPE

The objective of this SOW is to assess the feasibility of increasing power levels that can be applied to small, magnetically coupled thruster assemblies and to provide recommendations for specific solutions to increasing the performance of magnetically coupled thruster assemblies. These will be presented in the form of deliverables so that designers can use this information in the creation of prototypes for testing and evaluation of the design solutions.

The work will be focused on ways to improve the design of thruster assemblies utilizing magnetic fields to transfer power from an electric motor to a rotating propulsion shaft. The work will also focus on improving the design of associated bearings and other parts that may be exposed to the underwater environment. The trend toward quieter vehicles, and therefore quieter propulsion shaft bearings, is recognized as a major future design goal.

Several problems exist with current designs of magnetically coupled thrusters. The limitations of these thruster assemblies fall into 3 categories:

- Torque limitations within size restrictions.
- Rotational Speed limitations
- Abbreviated life of propeller shaft support bearings

This statement of work is designed around these limitations and shall address these problem areas.

4. REQUIREMENTS

The contractor's proposal shall identify from an overview how to approach each problem technically, alternative approaches, additional problems, costs and schedules, and recommendations for prototyping.

The contractor shall examine existing designs of magnetically coupled thruster assemblies and recommend design and/or procedural solutions to these problems so that

they can be implemented at a later date for testing and/or evaluation purposes. These solutions will be in the form of deliverables described later in this section of the SOW. The deliverables shall reflect the current state-of-the-art technology, and assume implementation within the next five to seven years.

4.1 Critical Design Areas

The overall objective is reliable longer-term deployment of ROVs/AUVs than is possible with current vehicle designs. Several specific critical areas have been identified which must be addressed in order to improve performance to an acceptable level. In dealing with specific design recommendations for maximizing system performance, the contractor must keep in mind that these must be based on the realization that compromise is an inevitable part of every design effort. Therefore, an indication of the relative importance of the recommendations must be provided as well as reasonable information on the application (and possible consequences) of less than optimum alternatives.

Consideration shall be given to the effect of noise reduction criteria on system design and resulting reliability to provide the designer with adequate information to properly evaluate the consequences of the trade-offs involved.

4.1.1 Torque vs Size, Weight and Fragility

The magnetically coupled thruster assemblies in use today are fairly large, particularly where higher than normal torque forces are required. In particular, the materials used in the past, require inordinately long coupling housings in order to deliver high levels of torque to the shaft. New materials may be available at present that will allow the use of shorter, more compact coupling assemblies. These potential improvements may allow shorter thrusters overall while delivering greater torque than has been possible in the past.

It is known that there are further limitations to the materials used in the past for magnetically coupled thrusters. Sumarium cobalt is a fragile material; Gaudolinium is somewhat stronger magnetically; some rare earth materials are not resistant to high temperatures.

The contractor shall investigate and recommend in the final report (CDRL item #A003), reliable materials that will increase the torque performance of existing magnetically coupled thruster designs.

4.1.2 Speed

There are further limitations to the performance of magnetically coupled thruster assemblies in terms of rotational shaft speed. Historically, in order to make housings for magnetically coupled thrusters used in deep water (greater than 1000 feet) strong and pressure proof, the materials for these housing are typically metallic and have been chosen for their high resistivity.

In using metals (or other conducting materials), designers have found that magnetic inductance from the rotating couplings induces eddy currents in the housing materials resulting in heat buildup. Most designs of this type also have a tangential speed limitation of approximately 5 feet per second even when using relatively high resistivity metallic materials such as hastelloy.

The contractor shall evaluate and recommend in the final report (CDRL item #A003), new housing materials that will substantially improve, or eliminate, rotational speed limitations and inductance heat buildup in magnetically coupled thruster assemblies.

4.1.3 Bearings in Sea Water

Another drawback to the use of magnetically coupled thruster assemblies is the exposure of bearing assemblies to the environment. This creates an undesirable corrosion problem in the bearing assemblies which necessitates undesirable frequencies of maintenance. An added performance problem for many applications is the added acoustic output of these bearing assemblies immersed directly in seawater.

A design that utilizes magnetic bearings may eliminate the requirements for bearings exposed to sea water and still allow the shaft to be exposed to seawater without corrosion or acoustic problems.

The contractor shall provide design recommendations in the final report (CDRL #A003), for magnetic bearings for use on the secondary coupling component in magnetically coupled thruster assemblies.

4.1.4 Other Potential Design Problems

There may be other potential problems encountered in high performance magnetically coupled thruster design. The contractor shall detail any other problems of concern and provide potential solutions for these problems in the final report (CDRL item #A003).

4.1.5 Prototyping Plan

If the results of the solutions to the problems identified above (and by the contractor) are favorable, and an overall assessment of the feasibility of increasing power levels that can be applied to small, magnetically coupled thruster assemblies is promising, prototyping of the design efforts will likely be pursued. The contractor shall provide a plan for prototyping of the designs developed under this phase (including cost and schedule). This effort may be performed in the second phase of this SOW as an option. The prototyping plan shall be submitted separately from the final report as (CDRL item #A004).

5.0 DELIVERABLES

The deliverables on this project shall be in contractor format and in accordance with the attached Contract Data Requirements List (CDRL), Form DD1423. The details of the required deliverables are as follows:

5.1 Program Plan (A001)

The contractor shall develop a program plan in accordance with CDRL #A001 identifying how to approach each problem technically (including breakpoints), alternative approaches, and a schedule for each required deliverable in Section 4 of this SOW. The plan shall elaborate on the contractor's proposed technical approach to the SOW and detail how the contractor will perform each required item within the allocated time and cost. A draft program plan shall be delivered 30 days after contract award, and is subject to Government approval. A final version of the program plan, with Government comments incorporated, shall be required 15 days after the contractor's receipt of the Government's comments.

5.2 Status Reports (A002)

The contractor shall provide project status in accordance with CDRL item #A002 by the fifteenth of each month for the previous calendar month.

5.3 Final Report (A003)

A draft final report prepared in accordance with CDRL item #A003, describing all research results and conclusions, shall be submitted 60 days prior to completion of the contract for review and comment.

A final report updating the draft report, as required by the review comments, shall be submitted 30 days after the contractor's receipt of the Government's comments on the draft report.

Specific deliverables to be included in the final report are the following:

5.3.1 Problem Documentation

Section 4 requires the contractor to provide evaluations, specifications, design guidelines, comparisons, descriptions and/or recommendations for each specific problem and to include the results as separate, identifiable items in the final report. The results shall be prepared in accordance with CDRL item #A003 for the ROV/AUV Magnetic Coupled Thruster tasking as directed in items 4.1.1 through 4.1.4 inclusive. The specific items to be reported are:

(4.1.1) Torque vs. Size, Weight and Fragility

The contractor shall investigate and recommend reliable materials that will increase the torque performance of existing magnetically coupled thruster designs.

(4.1.2) Speed and Temperature

The contractor shall evaluate and recommend new housing materials that will improve on, or eliminate rotational speed limitations and heat buildup in the housings of magnetically coupled thruster assemblies.

(4.1.3) Bearings in Sea Water

The contractor shall provide design recommendations for magnetic bearings for use on the secondary coupling component in magnetically coupled thruster assemblies.

(4.1.4) Other Design Problems

The contractor shall detail and provide detailed potential solutions for these problems in the final report.

5.4 Prototyping Plan (A004)

The contractor shall provide a draft plan for prototyping the designs developed in this phase of the SOW. The plan shall be subject to government approval. A final version will be required 15 days after receipt of government comments.

STATEMENT OF WORK

FOR

High Reliability Remotely Operated Vehicle (ROV)

Suspect Manufacturing Processes

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(ONR Code 122)

TABLE OF CONTENTS

STATEMENT OF WORK

1. BACKGROUND AND INTRODUCTION

In the future the U.S. Navy shall require the use of ROV systems for prolonged deployments. Toward this goal the government would like to compile a comprehensive list of manufacturing errors encountered in past ROV manufacturing operations which may have affected the reliability of the product. This comprehensive list shall be provided to ROV manufacturers to aid in production of more reliable ROV systems.

Every manufacturer of ROV systems and ancillary equipment has experienced manufacturing errors and production design problems which have adversely affected the reliability of the final product. These errors range over a wide spectrum of manufacturing processes from failure to reinspect certified incoming subassemblies and components to inadvertently exposing certain materials to a solvent that had detrimental effect on the material months later. Knowledge of all of these errors can assist a manufacturer in providing a more reliable product in the future.

The most knowledgeable and capable contractors to assemble a comprehensive list of these problems are the manufacturers. It is anticipated that manufacturers have records and knowledge of a variety of manufacturing problems and production design errors that have been eliminated for improvement of product reliability.

2. SCOPE

The objective of this contract is to identify problems that have caused errors in the manufacturing of ROV systems. These problems shall be identified, categorized and presented in the form of non-attributable deliverables for the use in the creation of new vehicles and systems, or in troubleshooting/retrofitting existing systems. The effort shall be focused on identifying the manufacturing errors that have occurred in ROV systems even with adequate QA-QC processes.

3. REQUIREMENTS

The contractor shall examine and identify from an overview all ROV manufacturing problems that have been observed by the manufacturers and their subcontractors. Included in this examination shall be alternative approaches, and expected solutions devised to correct the problems. The contractor shall categorize the manufacturing errors and recommend procedural solutions to these problems so that they can be avoided in the manufacturing of future high

reliability ROV systems. These recommendations shall be in the form of deliverables to this contract. The deliverables shall reflect the current state-of-the-art technology, and assume implementation in the next five years.

3.1 Critical Manufacturing Problem Areas

In dealing with specific manufacturing recommendations for maximizing system reliability, the contractor must keep in mind that these must be based on the understanding that eliminating the large majority of these problems does not necessarily require major restructuring of the manufacturing process. It is expected that recognition of many of the problems shall be sufficient for the manufacturer to avoid them.

3.1.1 Problems with Working Systems

ROV systems produced in the past have experienced reliability problems resulting from production design and manufacturing problems. Many of these problems were identified by the users and in many cases the user contacted the manufacturer with full descriptions of the problem. The contractor shall outline these problems, their cause as it relates to manufacturing and production design and their solutions. The contractor shall identify and categorize any such problems and provide recommendations/solutions for them in the final report.

3.1.2 Vehicles of Recent Manufacture

There are a variety of ROV systems that have been recently (within three years) produced which have a limited time in the field. These would include systems that, although not yet accepted by the customer, are still undergoing trials in the field at the present time. Many of the major ROV manufacturers have products in this stage of production. Many of these systems have experienced faults that may be a result of production design problems and/or manufacturing errors. As in item 3.1.1 above, these failures may be detailed in reports on operations and/or communications with either the manufacturer or technical support group for the system. The contractor shall identify and categorize those reliability problems and provide recommendations/solutions in the final report.

3.1.3 Vehicles Presently in Production

ROV systems that are in production at the present time also demonstrate reliability problems that are a result of faulty production design or other manufacturing problems. Most of the manufacturing errors that occur

with vehicles currently in production become known through quality testing procedures for the final system. Testing procedures that include vibration and shock tests, environmental tests, and pressure tests often bring manufacturing errors to light before the system experiences field trials. The contractor shall identify and categorize any manufacturing errors that have been identified for ROV systems still in the production process. Further, the contractor shall provide these categorizations and recommendations and/or potential solutions in the final report.

4. DELIVERABLES

The deliverable for this project shall be in the contractor format and in accordance with the attached Contract Data Requirements List (CDRL), form DD 1423. Details for the required deliverable follow:

The deliverable for this contract shall include lists of all the ROV reliability problems, of which the contractor is aware, arising from problems in the manufacturing and/or production design process. Recommendations/solutions to these problems shall also be detailed for each problem area. These lists should be categorized by manufacturing/production processes within the three major groupings of vehicle field history.

The deliverable for this contract shall be in the form of a final report, CDRL Item # A001, including the above lists and categories. This report will be compiled with the final reports from the other manufacturing contractors for the government by Marine Imaging Systems. During this compilation the identification of contractors contributing to the report and the identification of specific ROV systems shall be eliminated thus making the individual problems outlined generic and anonymous in the final compilation.

This compilation shall be made available to the manufacturing contributors to this effort. This will provide to the contributors listings of major manufacturing errors, production design problems and recommendations/solutions to these problems, so that they may avoid these problems in future manufacturing efforts.

4.1 Final Report (A001)

The final report, CDRL Item # A001, shall outline ROV reliability problems which stem from manufacturing errors. These errors/problems shall be categorized by vehicle field history as described in Sections 3.1.1 through 3.1.3 of this Statement of Work. The problems shall be further sub-categorized by production processes within each major category. For each problem area (or each individual problem

if appropriate) recommendations/solutions to the problem as they relate to manufacturing or production design shall be outlined.

A draft final report prepared in contractor format, describing all results and conclusions, shall be submitted 60 days prior to completion of the contract for review and comment. A final report updating the draft report, as required by the review comments, shall be submitted 30 days after the contractors receipt of the review comments on the draft report.

Specific deliverables to be included in the final report are:

4.1.1(3.1.1) Problems with Working Systems

The contractor shall identify and categorize any manufacturing related failures to ROV systems which have a significant field history and provide recommendations/solutions for them in the final report.

4.1.2(3.1.2) Vehicles of Recent Manufacture

The contractor shall identify and categorize those reliability problems attributable to production designs and/or manufacturing errors which have occurred with vehicles of recent manufacture and provide recommendations/solutions in the final report.

4.1.3(3.1.3) Vehicles Presently in Production

The contractor shall identify and categorize any manufacturing errors that have been identified for ROV systems still in the production process. Further, the contractor shall provide these categorizations and recommendations and/or potential solutions in the final report.

STATEMENT OF WORK

FOR

High Reliability Remotely Operated Vehicle (ROV)

and Autonomous Underwater Vehicle (AUV)

Buoyancy Materials

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Prepared For:

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Warfare Technologies Division
(ONR Code 122)

TABLE OF CONTENTS

STATEMENT OF WORK

1. BACKGROUND AND INTRODUCTION

Future Navy requirements will involve protracted deployments of underwater Remotely Operated Vehicles (ROVs) and Autonomous Untethered Vehicles (AUVs). To date, the performance of such vehicles has been heavily dependent on the quality and quantity of the maintenance and support available during relatively limited deployments. An ROV design that is appropriate for industrial (e.g., petroleum industry) operations, with limited exposure and the expectation of much maintenance, as a tradeoff against higher initial cost, is inappropriate for military missions with little or no opportunity for upkeep. As a result, the common practice of modifying existing ROVs and ROV subsystems for use in military service is undesirable and is not considered to be a long term solution for extended mission Navy operations.

The following operational capabilities and reliability goals need to be achieved for the Navy to meet its long term deployment ROV/AUV requirements. The vehicles must be designed and built to achieve an operational reliability of 98% or better when operating during protracted deployments (3-6 months wet or in a powered-down configuration for one to two months followed by weeks of subsequent operations). The ROV/AUV system operational capabilities to be considered are as follows:

1. The operational depth design considerations are maximums of 3,000 feet, 6,000 feet and 20,000 feet.

2. Tethers:

   A. The ROV system shall have a 4,000 foot powered tether working from a station keeping platform with a maximum distance from the platform of 3,000 feet in any direction. Station keeping is defined as zero relative velocity between platform and the surrounding water.

   B. The AUV shall have no tether.

3. The ROV or AUV system shall have low self-radiated noise according to the goals shown in Figure 1, and its auxiliary acoustic components shall not interfere with the platform sensors. The entire system shall minimize acoustic radiation.

4. The ROV or AUV system's magnetics shall not interfere with the platform or its sensors.

5. The ROV's capacity for a variety of work tasks, including heavy duty work and high power manipulators, shall also be considered.

6. The ROV's or AUV's maximum nominal speed shall be 5 knots.

All aspects of the system life cycle that may offset reliability were considered in an initial investigation, including; design, procurement practices, fabrication, inspection, in-service use and maintenance. The reliability problems identified in the investigation report covered the entire development phases of design, manufacturing and in-service life. The in-service life phase, concerned with training, maintenance and documentation are not to be considered under the tasking of this SOW, but later on as part of a specific system design. The focus of this SOW is on the application of technology to improve reliability.

Specifically, this statement of work addresses ROV/AUV syntactic foam buoyancy modules design and reliability problems and how their design and manufacture might be improved to help obtain the long range Navy objective of achieving a substantial increase in the extended mission reliability of ROVs/AUVs.

2.0 APPLICABLE DOCUMENTS

2.1 Other Government Documents

The following government document forms a part of this specification to the extent specified herein:

Syntactic Buoyancy Material for High Hydrostatic Pressures, MIL-S-24154A (SHIPS)

3. SCOPE

The objective of this Statement of Work is to provide recommendations for specific solutions to long term failures exhibited by standard formulations of syntactic foam buoyancy modules. This will be provided in the form of deliverables which will allow the designer of ROV/AUV systems with a basis for selecting reliable syntactic foam modules when designing new vehicles or in retrofitting existing systems.

The work shall be focused on ways to improve the reliability of syntactic foams. Although the use of commercially available syntactic appears to be the best choice for buoyancy materials at present, better performing materials shall be required for high reliability underwater systems in the near future. Many of the foams currently available today exhibit long term unreliability due to failures in the

structural makeup of the foam matrix. Failures that have been noted frequently in the past include physical breakdown of the individual modules. This most often occurs when the material has been subject to shock or impact.

4. REQUIREMENTS

The contractor's proposal shall identify from an overview how to approach each problem of syntactic foam unreliability technically, alternative approaches, costs and schedules. The approach shall address the major failure modes of syntactic foam modules, those being structural failure experienced by cracking and chipping and water absorption as a result of microsphere failure and improper formulation of the foam itself. These major failure modes can be caused by problems occurring in the three areas of design, manufacturing and testing.

The genesis of the results of the work in this Statement of Work shall generate a new specification for design, manufacture and testing of high reliability, long-term deployment syntactic foam capable of three depth regimes of 3,000, 6,000 and 20,000 feet.

The contractor shall examine these common failure modes and recommend design and/or procedural solutions to these problems so that they can be implemented at a later date for testing and/or examination purposes. These solutions shall be in the form of deliverables described later in this section of the SOW. The deliverables shall reflect the current state-of-the-art technology, and assume implementation in the next five years.

4.1 Syntactic Foam Performance

Microspheres within a resin matrix are commonly used for buoyancy in the underwater environment for use on manned and unmanned submersibles. The small spheres do not exhibit high energy release upon failure because, individually, they do not have any appreciable kinetic energy at depth and they do not often fail simultaneously. Also, because of their small size, they have very small interstitial spaces. Binary blends of the microspheres with a mixture of two sizes (1x dia and 7x dia) create a nearly perfect fill and minimize the interstitial spaces as well.

Syntactic foam is produced in varying densities, with the denser foams (which generally have smaller gas-filled spheres) being rated for deeper depths. These "deeper" foams inherently have less buoyancy per volume than the less dense, shallower rated foams.

Unfortunately, many designs of syntactic foam in production today exhibit undesirable characteristics such as cracking and chipping under physical abuse and water pickup after prolonged exposure to high hydrostatic pressure. Cracking and chipping results from low strength in the binding agents. Water pickup is most often caused by the wall failure of microspheres located tangential or very close to the outside of the syntactic foam unit as well as water penetration into "voids" in the binding agents. When foam blocks chip or crack more of the materials surface area is exposed to the underwater environment and as a result, some amount of buoyancy is lost. Another failure exhibited by existing formulations of syntactic foam is the failure of the structure of "microspheres" which are the main buoyancy component of the modules. Under pressure and over long periods of time, wall failure of these small buoyancy components result in a loss of buoyancy of the system. Further loss of buoyancy over the long term results from a similar "water pickup" due to "macro voids" in the binding agents used in the formulation of the modules

It has been known that even the higher quality syntactic foam formulations demonstrate water absorption to a minimum of .10" to all exposed surfaces of the modules. This occurs because the microspheres at the surface are not fully encapsulated and collapse under pressure. This action results in a permanent loss of buoyancy for the overall module. This penetration occurs very rapidly under pressure and most foams will exhibit at least 50% of its total lifetime water absorption within 48 hours at pressure. This level of water absorption is acceptable in most buoyancy applications but further water pickup is unacceptable and contributes to the lack of reliability of the product.

The expected solution for high reliability buoyancy components would be to develop and use a very high performance foam that has special features (binary blended microspheres, pre-pressurized microspheres, high strength, low density binding compounds, etc). This approach has the potential to keep the size and weight of syntactic buoyancy systems under control. To insure the final product is maintained with the design guidelines, further steps of implementing a rigorous Quality Assurance procedure at every step of manufacturing and testing are required.

4.2 Design

A reliably performing foam should be designed that does not exhibit the common failure modes of existing foams. The design process shall address all the major components of buoyancy modules for use in the underwater environment.

4.2.1. Glass Microspheres

Sources for glass microspheres have been limited in the past to one or two suppliers. This can severely limit the availability of production of acceptable products for the government. The contractor shall investigate both additional sources of glass microsphere and the possibility of other, more readily available materials for use in syntactic foam.

4.2.2. Resin Binders

The resin binder component in syntactic foam is a crucial part of the modular unit and has the greatest potential for design improvements. With a strong, low density binder structural failure of the final product can be minimized. The contractor shall recommend design improvements to existing formulations of binding materials for use in a high performance syntactic foam.

4.2.2.1 Bulk Modulus

The binder is often the component that dictates, to a large part, the three directional compressibility or bulk modulus of the final product. In order to minimize the requirements for large ballasting systems on underwater vehicles, the ideal buoyancy component of the system would have a modulus similar to that of seawater. This would allow the buoyancy modules to maintain the same buoyancy throughout the rated working depth of the system. The contractor shall recommend syntactic foam formulations that have suitable bulk modulus for use at 3,000, 6,000 and 20,000 foot depths. Recommendations shall be provided in the final report (CDRL item #A003).

4.2.2.2 Fillers

Low density fibers and other fillers in the resin body of syntactic foam can degrade its performance and strength over long periods of time. The contractor shall design resin binders that do not contain fillers to lower its density. The design shall be provided in the final report (CDRL item #A003).

4.2.2.3 Hazardous Materials

Some formulations of binders contain potential hazardous materials. The removal of these compounds from the manufacturing process may affect the availability of the final product until a substitute can be found. The contractor shall investigate formulations that do not require potentially

hazardous materials and he shall further identify potential replacements for any materials in question in the final report (CDRL item #A003).

4.2.2.4 Exothermic Properties

Most resin binders used in the production of syntactic foams possess exothermic properties which, unless carefully controlled, can result in a non-homogenous product. Also, exothermic reactions can prevent small test runs of a product from accurately representing the final product run in larger volumes. The contractor shall investigate the possibility of using binders that do not possess exothermic properties during the manufacturing process. If less exothermic material is found, the contractor shall recommend control of production process during manufacture. Recommendations shall be provided in the final report (CDRL item #A003).

4.2.3. Coatings

On many formulations of syntactic foam, protective coatings have been applied to the modules outer surface. These coatings, when used on a water blocking material, can fail and significantly degrade the performance of the foam. Although protective coatings can be valuable to enhance the shock absorbing qualities of the final product, these coatings should not block water from contacting the outer surface of the foam proper, since water blocking coatings are a short term, stop gap measure to prevent water pick up in buoyancy modules. Further these coatings should be of low density, but elastic enough and strong enough to protect the modules from shock. The contractor shall recommend protective coatings for high performance syntactic foam that provide effective shock absorbing qualities without waterproofing the surface of the foam modules. The recommendation shall be provided in the final report (CDRL item #A003).

4.2.4. Macrospheres

In lower density, shallower rated foams larger spheres called "macrospheres" are often used. The materials, construction and size of these macrospheres can have an important impact on the performance of the final product. The contractor shall recommend high performing materials, design and size of macrospheres for optimum performance in the final syntactic foam product and provide the recommendations in the final report (CDRL item #A003).

4.2.5. Fasteners

In assembling final production modules of syntactic foam to an underwater vehicle system, very often a variety of adhesives and fasteners must be used. These fasteners must be reliable and perform over long term deployments. The contractor shall recommend types and designs of fasteners and adhesives to be used in the final assembly of the buoyancy components to the finished system. Recommendations shall be provided in the final report (CDRL item #A003).

4.3. Manufacturing

In the manufacturing process there are a number of processes that can improve the reliability of syntactic foam. Syntactic foam has been manufactured in a number of different ways including mixing a viscous formulation and vacuum injection. It is desirable during manufacture to create a homogeneous, consistent product which exhibits the optimum characteristics of low density and high strength. The contractor shall provide the recommendations on the optimum processes in the final report (CDRL item #A003).

4.3.1. Microspheres

In the production of microspheres, a great variety of product is typically found. Selecting the appropriate size and strength product has an important impact on the performance of the syntactic with which they are made. The contractor shall investigate and recommend methods by which the final microspheres used in the manufacture of the syntactic foam are selected. Recommendations shall be provided in the final report (CDRL item #A003).

4.3.2. Packing Factor

The distribution of microspheres within a manufactured block of final product can affect the quality and performance of the final product. In some manufacturing methods, the microspheres will shift while the formula is still in a slightly viscous state. This does not provide an even distribution of the microspheres and prevents the product from having a uniform density. The contractor shall recommend methods of packing the spheres within the mold for the final product to include the maximum quantity of microspheres. Additionally, he shall recommend methods to prevent the microspheres from shifting within the formula before it has hardened. The recommendations shall be provided in the final report (CDRL item #A003).

4.3.3. Adherence

Many formulations of binding agents do not lend themselves to adhering to the microspheres within the product. This can lead to a lower than desired strength foam as well as voids within the foam module. The contractor shall recommend methods to aid adherence of the resin to the microspheres to maximize the strength of the final product. Recommendations shall be provided in the final report (CDRL item #A003).

4.3.4. Macrospheres

The placement of macrospheres in foams that require them is important to the performance of the product. The contractor shall recommend manufacturing methods to assure that the packing and positioning of the macrospheres is optimum and shifting does not occur during the manufacturing process. Recommendations shall be provided in the final report (CDRL item #A003).

4.4. Testing

In the manufacture of syntactic foams, a variety of tests is required to ensure a reliable product. These tests must be designed to evaluate the product properly or the results can be misleading. If the buoyancy test of the product is based on weight alone, a loss of buoyancy due to permanent compression during pressure test may be overlooked.

4.4.1. Test Samples

Common methods of sampling production units of syntactic foam do not adequately represent the final manufactured product. The contractor shall recommend sampling methods that provide samples that are representative of the final product. Recommendations shall be provided in the final report (CDRL item #A003).

4.4.2. Displacement Testing Under Pressure

Experience has shown that representative samples should be tested to show long-term buoyancy performance in one test rather than in two separate tests which evidence weight gain and changes in size. The contractor shall recommend short-term, long-term and accelerated high pressure testing methods, which provide accurate, continual data during the production, on displacement and buoyancy of syntactic foam test samples. Recommendations shall be provided in the final report (CDRL item #A003).

4.4.3. Fasteners

Failure modes in many syntactic foam blocks have occurred due to unreliable nonmetallic adhesives and fasteners used in joining or attaching syntactic foam modules to other components. The contractor shall recommend test procedures to test adhesives and fasteners used in conjunction with the syntactic modules during final assembly to a submersible vehicle. Recommendations shall be provided in the final report (CDRL item #A003).

4.5 Other Potential Problems

The contractor shall provide recommendations for other problems that may be encountered by the syntactic foam user other than the problems listed above. There are many different syntactic foams now in use on Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs). Each of these foams has unique problems with respect to meeting the design specification and operational requirements other than those listed above. The contractor shall detail any other identified problems which may be of concern to design engineers. Potential solutions for these problems shall be provided in the final report (CDRL item #A003).

4.6 High Reliability Syntactic Foam Specification

The contractor shall develop a specification for construction of a high reliability, long term deployment syntactic foam for use on ROV/AUV systems. The specification shall address the problems listed above and those generated by the contractor, that are associated with syntactic foams used at deep ocean depths with emphasis on the depths of 3,000 feet, 6,000 feet and 20,000 feet. The contractor shall provide this specification separate from the final report (CDRL item #A004).

4.7 New Materials

The contractor shall assess new materials that are available to substitute for syntactic foam, including the advantages/disadvantages, status of the associated technology and degree of promise. The potential new materials assessment shall be included in the final report (CDRL item #A003).

4.8 Design Testing

The contractor shall identify and recommend in this SOW any concept definiticn design testing that should be undertaken and the associated advantages of that testing in validating the High Reliability Syntactic Foam Specification. The concept definition design testing description shall include the cost and schedule impact. The recommendation shall be included in the final report (CDRL item #A003).

5.0 DELIVERABLES

Evaluations, specifications, design guidelines, comparisons, descriptions and/or recommendations for the specific technical problems of buoyancy materials shall be a prime product (CDRL item #A003). The contractor shall provide a specification for high reliability syntactic foam as a deliverable on this contract (CDRL item #A004). The contractor shall provide a final report (CDRL item #A003). Other deliverables required are a program plan (CDRL item #A001), and status reports (CDRL item #A002).

The deliverables on this project shall be in contractor format and in accordance with the attached Contract Data Requirements List (CDRL), Form DD1423. The details of the required deliverables are as follows:

5.1 Program Plan (A001)

The contractor shall develop a program plan in accordance with CDRL item #A001, identifying how to approach each problem technically (including breakpoints), alternative approaches, and a schedule for each required deliverable in Section 4 of the SOW. The plan shall elaborate on the contractor's proposed technical approach to the SOW and detail how the contractor will perform each required item within the allocated time and cost. A draft program plan shall be delivered 30 days after contract award, and is subject to Government approval. A final version of the program plan, with Government comments incorporated, shall be required 15 days after the contractor's receipt of the Government's comments.

5.2 Status Reports (A002)

The contractor shall provide project status in accordance with CDRL item #A002 by the fifteenth of each month for the previous calendar month.

5.3 Final Report (A003)

A draft final report prepared in accordance with CDRL item #A003, describing all research results and conclusions, shall be submitted 60 days prior to completion of the

contract for review and comment.

A final report updating the draft report, as required by the review comments, shall be submitted 30 days after the contractor's receipt of the Government's comments on the draft report.

Specific deliverables to be included in the final report are the following:

5.3.1 Problem Documentation

Section 4 requires the contractor to provide evaluations, specifications, design guidelines, comparisons, descriptions and/or recommendations for each specific problem and to include the results as separate, identifiable items in the final report. The results shall be prepared in accordance with CDRL item #A003 for the ROV Buoyancy Materials tasking as directed in items 4.2.1 through 4.4.3 inclusive and items 4.5, 4.7, and 4.8. The specific items to be reported are:

(4.2.1) Glass Microspheres

The contractor shall investigate both additional sources of glass microspheres and the possibility of other, more readily available materials for use in syntactic foam.

(4.2.2) Resin Binders

The contractor shall recommend design improvements to existing formulations of binding materials for use in a high performance syntactic foam.

(4.2.2.1) Bulk Modulus

The contractor shall recommend syntactic foam formulations that have suitable bulk modulus for use at 3,000, 6,000 and 20,000 foot depths.

(4.2.2.2) Fillers

The contractor shall recommend resin binder formulae that do not contain fillers to lower its density.

(4.2.2.3) Hazardous Materials

The contractor shall investigate formulations that do not require potentially hazardous materials and he shall further identify potential replacements for

any materials in question.

(4.2.2.4) Exothermic Properties

The contractor shall investigate the possibility of using binders that do not possess exothermic properties during the manufacturing process. If less exothermic materials are found, the contractor shall recommend controls for the production process.

(4.2.3) Coatings

The contractor shall recommend protective coatings for high performance syntactic foam that provide effective shock absorbing qualities without waterproofing the surface of the foam modules.

(4.2.4) Macrospheres

The contractor shall recommend high performing materials, design and size for macrospheres that will provide optimum performance in the final syntactic foam product.

(4.2.5) Fasteners

The contractor shall recommend types and designs of fasteners and adhesives to be used in the final assembly of the buoyancy components to the finished system.

(4.3.1) Microspheres

The contractor shall investigate and recommend methods by which the final microspheres used in the manufacture of the syntactic foam are selected.

(4.3.2) Packing Factor

The contractor shall recommend methods of packing the spheres within the mold for the final product to include the maximum quantity of microspheres. Additionally, he shall recommend methods to prevent the microsphere from shifting within the formula before it has hardened.

(4.3.3) Adherence

The contractor shall recommend methods to aid in the adherence of the resin to the microspheres to maximize the strength of the final product.

(4.3.4) Macrospheres

The contractor shall recommend manufacturing methods to assure that the packing and positioning of the macrospheres is optimum and shift does not occur during the manufacturing process.

(4.4.1) Test Samples

The contractor shall recommend sampling methods that provide samples that are representative of the final product.

(4.4.2) Displacement Testing Under Pressure

The contractor shall recommend short term, long term and accelerated high pressure testing methods which provide accurate, continual data during the production run on displacement and buoyance of syntactic foam test samples.

(4.4.3) Fasteners

The contractor shall recommend test procedures to test adhesives and fasteners used in conjunction with the syntactic modules during final assembly to a submersible vehicle.

(4.5) Other Potential Problems

The contractor shall detail and provide detailed potential solutions for these problems in the final report (CDRL item #A003).

(4.7) New Materials

The contractor shall assess new materials that are available to substitute for syntactic foam.

(4.8) Design Testing

The contractor shall identify any concept definition design testing that should be conducted in accordance of this SOW.

5.4 High Reliability Syntactic Foam Specification (A004)

The contractor shall develop a specification per paragraph (4.6) for construction of a high reliability, long term deployment syntactic foam for use on ROV/AUV systems. The depths of interest are 3,000 feet, 6,000 feet and 20,000 feet.

STATEMENT OF WORK

FOR

High Reliability Remotely Operated Vehicle (ROV)

and Autonomous Underwater Vehicle (AUV)

Sealing Systems

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TABLE OF CONTENTS

Section/Paragraph

STATEMENT OF WORK

1. BACKGROUND AND INTRODUCTION

Future Navy requirements shall involve protracted deployments of underwater Remotely Operated Vehicles (ROVs) and Autonomous Untethered Vehicles (AUVs). To date, the performance of such vehicles has been heavily dependent on the quality and quantity of the maintenance and support available during relatively limited deployments. An ROV design that is appropriate for industrial (e.g., petroleum industry) operations, with limited exposure and the expectation of much maintenance, as a tradeoff against higher initial cost, is inappropriate for military missions with little or no opportunity for upkeep. As a result, the common practice of modifying existing ROVs and ROV subsystems for long term, at-sea storage and/or operation without maintenance is undesirable and is not considered to be a long-term solution for extended mission Navy operations.

The following operational capabilities and reliability goals need to be achieved for the Navy to meet its long term deployment ROV/AUV requirements. The vehicles must be designed and built to achieve an operational reliability of 98% or better when operating during protracted deployments (3-6 months wet or in a powered-down configuration for one to two months followed by several weeks of subsequent operations). The ROV/AUV system operational capabilities to be considered are as follows:

1. The operational depth design considerations are maximums of 3,000 feet, 6,000 feet amd 20,000 feet.

2. Tethers:

   A. The ROV system shall have a 4,000 foot powered tether working from a station keeping platform with a maximum distance from the platform of 3,000 feet in any direction. Station keeping is defined as zero relative velocity between platform and geodetic and geographic surroundings.

   B. The AUV shall have no tether.

3. The ROV or AUV system shall have low self-radiated noise, according to the goals shown in Figure I, and its auxiliary acoustic components shall not interfere with the platform sensors. The entire system should minimize acoustic radiation.

4. The ROV or AUV system's magnetics shall not interfere with the platform or its sensors.

5. The ROV's capacity for a variety of work tasks, including heavy duty work and high power manipulators, shall also be considered.

6. The ROV's or AUV's maximum nominal speed shall be 5 knots.

All aspects of the system life cycle that may offset reliability were considered in an initial investigation, including; design, procurement practices, fabrication, inspection, in-service use and maintenance. The reliability problems identified in the investigation report covered the entire development phases of design, manufacturing and in-service life. The in-service life phase, concerned with training, maintenance and documentation are not to be considered under the tasking of this SOW, but later on as part of a specific system design. The focus of this SOW is on the application of technology to improve reliability.

Specifically, this statement of work addresses reliability problems with high pressure differential shaft seals used on vehicles and how their design might be improved to help obtain the long range Navy objective of achieving a substantial increase in the extended mission reliability of ROVs/AUV's.

2. SCOPE

The objective of this SOW is to provide recommendations for eliminating the chronic failures in sliding, rotating, hydraulic and static seals on ROV/AUV systems in the marine environment. This shall be presented in the form of deliverables so that designers can use this information in the creation of new vehicles and systems, or in troubleshooting/retrofitting existing systems.

The work shall be focused on ways to improve the reliability of seals, including the static and moving components of these sealing assemblies. The design of elaborate, compensated seal assemblies can, with a high reliability ROV/AUV, drive up the size and complexity of the vehicle subcomponents. Consequently, the contractor shall conduct design tradeoffs to select the optimum seal design characteristics affording the desired reliability level in a small size.

For electronics housing endcaps, mechanical hull penetration components (rotating or sliding) and cable terminations on ROV/AUV systems, effective mechanics for seal barriers are very important for overall system reliability. Areas where these seals are used include thruster assemblies and actuator rod seals. It has been the experience of vehicle system designers and users that although all of these areas

are potential failure points, some are more reliable than others.

Many seals are largely static and experience very little friction. An example of this is the standard "O" or "X" ring seal used on electronic housing endcaps. Often the only movement these seals experience other than when removing or replacing the seals themselves, is caused by the pumping action resulting from cycling through high pressure environments.. However, these components do breakdown over time and require consideration during system design. Dual seals of different types such as face seals for high pressure environments and radial seals for low pressure environments are often designed into systems to increase their overall reliability.

However, seals that experience high levels of friction, such as moving shaft seals, more significantly contribute to reliability problems primarily due to the increased wear which they experience. Seals across which there is a high pressure differential are found on a number of parts of underwater vehicles and are of particular concern, in that with time, their reliability drops dramatically. Specifically, the seal reliability must be increased for hydraulic and air-backed thruster assemblies and any other components on the ROV/AUV system which utilizes high friction seals.

3. REQUIREMENTS

The contractors proposal shall identify from an overview how to approach each problem technically, alternative approaches, costs and schedules.

The contractor shall examine and develop solutions to common failure modes of seals in the marine environment and recommend design and/or procedural solutions to these problems so that they can be implemented at a later date for testing and/or evaluation purposes. These solutions shall be in the form of deliverables described later in this section of the SOW. The deliverables shall reflect the current state-of-the-art technology, and assume implementation in the next five years.

3.1 Critical Design Areas

The overall objective is reliable longer-term deployment of ROVs/AUVs than is possible with current commercial vehicle designs modified to meet Navy requirements. Several specific critical areas have been identified which must be addressed in order to improve reliability to an acceptable level. In dealing with specific design recommendations for maximizing system reliability, the contractor must keep in

mind that these must be based on the realization that compromise is an inevitable part of every design effort. Consequently, the importance of each recommendation, relative to other recommendations, must be indicated. Further, the contractor shall provide reasonable comparison information on the application of less than optimum alternatives and their possible consequences.

Specific consideration shall be given to the environment in which this ROV/AUV shall be performing. The pressures are not expected to exceed 1500 psia but there may be significant pressure cycling during active and inactive periods. There may also be long periods (up to 90 days) of inactivity after which the system is expected to function at any pressure within the rated range. Consideration shall also be given to seals operating in the 3000 psia and 10,000 psia pressure ranges.

The design of most long life, noncompensated seals require some form of lubrication for both cooling and friction reduction. Since the reliability of an ROV/AUV may be adversely affected by even small amounts of water intrusion, a compensated seal design is likely to be more desirable than a non compensated seal design in high friction, high differential pressure conditions. However, tradeoffs exist between the use of compensated or non compensated seal designs particularly in the areas of failure and maintenance. The contractor shall examine the tradeoffs in the application of these two designs in terms of MTTR and MTBF figures.

3.2. High Friction Seal Design

Due to the complexity of the construction, a variety of seal designs for rotating and sliding compensated seals are possible. The contractor shall compare the different methods and recommend the most reliable method of compensating and integrating the seal within the housing which the shaft penetrates. It is expected that there shall be no allowance for water intrusion into the housing being sealed. If the final design of the seal absolutely requires leakage for seal lubrication and increased reliability, the contractor must realize that it is preferable in this situation to have a small amount of lubricant leak out into the environment rather than water leak into the sealed component.

3.2.1. High Friction Seal Carrier Assembly Materials

Corrosion adversely affects the reliability of any underwater system. The design and construction of a seal system for use on a long-term deployable ROV/AUV system must take the problems of various types of corrosion into account. The contractor shall design a seal that may be constructed from stainless steel,

Inconel, titanium or other alloy resistant to corrosion and provide the design in the final report (CDRL item #A003). If the material of choice for the seal system has distinct advantages over other materials, it is understood that its use may drive the choice of material for the sealed housing.

3.2.2. High Friction Sealing Face Materials

For seal systems, the materials used most often are a composite material that shall perform reliably under high rpm rotation conditions. The contractor shall examine all possible materials for the seal face including graphites and ceramics such as tungsten or silicon carbide as well as any other material which may perform reliably. The contractor shall recommend the material in the final report (CDRL item #A003) that will provide the highest reliability.

3.2.3. Acoustic Output

The ROV/AUV systems employing high reliability seals for high friction applications shall be designed to have minimal acoustic output during operation. Bearing assemblies contained within some sealing systems may contribute significantly to overall acoustic output. The contractor shall recommend bearing designs that have a low noise signature while maintaining positive bearing qualities for wear, strength and corrosion resistance and provide these recommendations in the final report (CDRL item #A003).

3.2.4. Operating Ranges

Seal systems are typically comprised of a number of machined parts with close tolerances. The reliability of the seal system relies, in part, on the precision with which these parts fit together. Some of these parts are susceptible to physical changes with varying temperature which could adversely affect the reliability of the sealing system. The contractor shall provide the tradeoffs involved, if any, of choosing materials that shall not be adversely affected by operating in underwater environments ranging from -2^{o} to $40^{o}C$, and provide the results in the final report (CDRL item #A003).

3.2.5. Torque Requirements

An increase in pressure across any shaft seal face typically increases the torque required to both initiate movement and in the case of extension and rotary shafts, maintain movement of the shaft. Since the new seal design may be applied to torque sensitive

electric motors, the contractor shall provide a seal design that does not significantly contribute to the normal torque required to initiate movement and continue movement. The contractor shall provide the results in the final report (CDRL item #A003).

3.2.6. Test Plan

Since these high friction seals may experience continual changes in ambient pressures, a test plan is required. The following test plan shall be developed to determine the performance of the seal for long-term deployment as well as for 1000 cycles from one atmosphere absolute to rated working pressure and return, with particular attention to long-term wet storage of the ROV/AUV system and extended power-down periods.

3.2.6.1. Leak Rates

The contractor shall draft a test plan for the prototype to determine that the seal design demonstrates minimal or no leakage through cycling and over the long term. The leak rates shall be quantifiable during this period. The contractor shall provide the results in the final report (CDRL item #A003).

3.2.6.2. Torque

The contractor shall draft a plan for testing the prototype unit's torque required over the full range of rated working pressure for both startup and continuance of shaft movement, and provide the results in the final report (CDRL item #A003).

3.2.6.3. Long-term Static Testing

The contractor shall draft a test plan for the prototype where the seal is inactive (no rotational or sliding motion) for up to 90 days after which the seal should function under working conditions, and provide the results in the final report (CDRL item #A003).

3.2.6.4. Acoustic Output

The contractor shall draft a test plan to determine the acoustic output of the seal assembly under realistic duration (active or inactive period (i.e. after a 90 day inactive period)) and throughout the rated working pressures of the seal assembly, and provide the results in the final report (CDRL item #A003).

3.2.6.5. Bearing Wear

The contractor shall draft a test plan to determine the bearing wear that shall be experienced by the seal assembly during the operation of the final system at various working pressures over the deployment duration (active or inactive period) and provide the results in the final report (CDRL item #A003).

3.2.6.6. Seal Face Wear

Since the heart of any sealing assembly is the high friction face area, the contractor shall draft a plan to test and quantify the seal face wear of the unit throughout the depth and duration of expected deployment (active or inactive period), and provide the plan in the final report (CDRL item #A003).

3.2.7. Prototype

A new high friction seal design for high reliability may require prototyping in order to test the various required qualities in the design. The contractor shall draft a proposal for building a prototype design in order to test the seal's performance for long-term deployment, and provide the plan in the final report (CDRL item #A003). This proposal may be executed as an option to this contract at the discretion of the Government.

3.3 Static Seals

High friction shaft seals frequently have secondary seals within the main seal carrying assembly and at the seal-housing joint which are referred to as "static" seals . These indirect seals , although not usually subject to high friction conditions, can be as crucial to the whole seal integrity as the main seal itself. The contractor shall minimize these indirect seals, in addition to trying and maximize their reliability and performance, during the design process. These static seals also are applied to housing endcaps, hydraulic joints, connector assemblies, cable terminations and other sealed assemblies.

3.3.1. Static Seal Materials

Given the pressures and cycling for which the ROV/AUV system shall be designed, the static seals shall be required to maintain their seal integrity over a fairly wide pressure range for more than 1000 cycles. The contractor shall investigate and recommend any new materials for these seal components that may be better suited to the application than those in common use, and provide the results in the final report (CDRL item #A003).

3.3.2. Static Seal Configuration

For static O-seals, face and radial configurations have tradeoffs and are often used together to increase reliability. Further, there may be other static seal designs and/or configurations, such as Quad-seals™ or the use of back-up rings, that may have more reliability than conventional O-seal installations. The contractor shall examine and recommend any of these sealing configurations that would be expected to increase the reliability of the overall seal system, and provide the results in the final report (CDRL item #A003).

3.3.3. Static Seal Compression Setting

The contractor shall consider the detrimental effects of seal and gasket compression setting caused by long term exposures to high pressure environments. The contractor shall recommend materials and configurations of the static seal components that do not demonstrate static seal compression setting, and provide the results in the final report (CDRL item #A003).

3.3.4 Cable Terminations

Effective cable terminations, particularly those integrated with cable strength members, can be a critical link in any underwater system. Regardless of the strength member integration, the seal for the ROV cable termination and high reliability system is commonly the weakest link in the cable assembly. The contractor shall evaluate all termination types currently in use and provide recommendations for high reliability terminating methods and designs in the final report (CDRL item #A003).

3.4 Reference Documentation

The contractor shall make a thorough survey of applicable military standards, specifications and handbooks. The contractor shall compile all such documents, cross-

referenced and explained so that the designer shall have a single, concise source for selection of applicable controlling documents to reference during the preparation of material, process, or product specifications. The contractor shall draw on these and other sources of information, and on his own experience in the design and implementation of underwater sealing systems of all types, and produce a compendium of specific guidelines on how to design to prevent problems (historical and expected) which plague ROV/AUV seals reliability. This compendium shall be presented as an attachment (CDRL item #A003) to the final report.

3.5 Manufacturing Errors

During the contract it is expected that the contractor shall develop a list of common manufacturing errors found to cause various types of sealing system failures. This list will be valuable in warning the ROV/AUV designer or manufacturer of their existence. The contractor shall make this list available as an attachment to the final report. The list of errors shall include explanations, desirable alternative solutions, and recommendations (CDRL item #A003).

4. DELIVERABLES

Design recommendations for the technical aspects of seal assemblies which contribute to failures shall be a prime product. The contractor shall provide a prototype seal design as part of the deliverable on this contract along with the test plan as outlined in section 3.2.6. (CDRL item #A003.) The contractor shall produce a compendium of specific design guidelines for preventing problems which plague ROV/AUV seals (CDRL item #A003). The contractor shall also provide a list of common manufacturing errors found to cause seal failures, and a final report (CDRL item #A003). Other deliverables required are a program plan (CDRL item #A001), and status reports (CDRL item #A002).

The deliverables on this project shall be in contractor format and in accordance with the attached Contract Data Requirements List (CDRL), Form DD1423. The details of the required deliverables are as follows:

4.1 Program Plan (A001)

The contractor shall develop a program plan in accordance with CDRL #A001 identifying: how to approach each problem technically (including breakpoints), alternative approaches, and a schedule for each required deliverable in section 4 of the SOW. The plan shall elaborate on the contractors proposed technical approach to the SOW and detail how the contractor shall perform each required item within the allocated time and cost. A draft program plan shall be delivered 30 days after contract award, and is subject to

Government approval. A final version of the program plan, with Government comments incorporated, shall be required 15 days after the contractors receipt of the Governments comments.

4.2 Project Status (A002)

The contractor shall provide project status in accordance with CDRL #A002 by the fifteenth of each month for the previous calendar month.

4.3 Final Report (A003)

A draft final report prepared in accordance with CDRL #A003, describing all research results and conclusions, shall be submitted 60 days prior to completion of the contract for review and comment.

A final report updating the draft report, as required by the review comments, shall be submitted 30 days after the contractors receipt of the Governments comments on the draft report.

Specific deliverables to be included in the final report are the following:

4.3.1 Problem Documentation (CDRL item #A003)

Section 3 requires the contractor to provide evaluations, designs, tradeoffs, and/or recommendations for each specific problem and to include the results as separate, identifiable items in the final report. The results shall be prepared in accordance with CDRL #A003 for the ROV/AUV shaft seal components, subsystems, supporting/auxiliary equipment or processes as directed in items 3.2.1 through 3.2.7. inclusive. The specific items to be reported are:

(3.2.1.) Seal Carrier Assembly Materials

The contractor shall provide designs for seal carriers that can be constructed of a variety of corrosion resistant materials. The contractor shall also recommend the best material from a manufacturing and reliability standpoint.

(3.2.2.) Seal Face Materials

The contractor shall provide the trade off and analyses for using a variety of materials in the seal face. The contractor shall also recommend the best material to be used in this part of the seal.

(3.2.3.) Acoustic Output

The contractor shall provide seal design recommendations for bearings assemblies that shall minimize the expected seal wear while maintaining a low noise signature.

(3.2.4.) Operating Ranges

The contractor shall provide seal design recommendations that shall perform well within the temperature and pressure ranges outlined.

(3.2.5.) Torque Requirements

The contractor shall provide seal design recommendations that shall require minimal torque for initial and continuing shaft movement in the operating environment.

(3.2.6.1) Leak Rates

The contractor shall provide a test plan for the prototype seal design to determine that it demonstrates minimal or no leakage. The leak rate shall be quantified with respect to pressure cycling and long-term deployment.

(3.2.6.2.) Torque

The contractor shall provide a test plan to measure the prototype seal design torque requirements throughout the rated working pressures of the seal.

(3.2.6.3.) Long-term Static Testing

The contractor shall provide a test plan for the prototype seal design to determine the effects of extended power-down periods on the effectiveness of the seal integrity.

(3.2.6.4.) Acoustic Output

The contractor shall provide a test plan to determine the seal assembly's contribution to radiated noise throughout rated working pressures and life cycle (active/inactive) of the seal assembly.

(3.2.6.5.) Bearing Wear

The contractor shall draft a test plan to determine the rate of wear which will be experienced by any bearing subassemblies in the seal design over its working life (active/inactive).

(3.2.6.6.) Seal Face Wear

The contractor shall provide a test plan to quantify the sealing face wear in a prototype design throughout the duration (active/inactive) and working depths of the system.

(3.2.7.) Prototype

The contractor shall provide a proposal for constructing prototype seal assemblies to test performance of the design. This proposal may be executed as an option to this contract at the discretion of the Government.

(3.3.1.) Static Seal Materials

The contractor shall provide recommendations and evaluations of any new materials that can be applied to static seals for use at the rated working pressures and deployment duration for a high reliability vehicle.

(3.3.2.) Static Seal Configuration

The contractor shall evaluate and recommend any new conceptual designs in radial, face or other static seal configuration that may be expected to increase the reliability of sub-components of a long-term deployed ROV/AUV system.

(3.3.3.) Static Seal Compression Setting

The contractor shall provide evaluations of materials and configurations of static seals that demonstrate minimal compression setting.

(3.3.4.) Cable Terminations

The contractor shall provide recommendations and evaluations of cable termination methods and designs for use on a high reliability ROV/AUV system.

4.3.2. Reference Documentation (A003)

The contractor shall provide a compendium of applicable literature and specific guidelines on how to design to prevent problems which plague ROV/AUV shaft seal reliability. The contractor shall make a thorough survey of applicable military standards, specifications and handbooks. He shall compile all such documents, cross-referenced and explained so that the designer will have a single, concise source for selection of applicable controlling documents to reference during

the preparation of material, process, or product specifications. (Item 3.4 Reference Documentation.)

4.3.3 Manufacturing Errors (A003)

The contractor shall provide a list of common seal assembly manufacturing errors including desirable alternative solutions and explanations. (Item 3.5 Manufacturing Errors.)

STATEMENT OF WORK

FOR

High Reliability Remotely Operated Vehicle (ROV)

Tether Assemblies

Prepared By:

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Prepared For:

Office of Naval Research (ONR)
Warfare Technologies Division
(ONR Code 122)

TABLE OF CONTENTS

Section/Paragraph

STATEMENT OF WORK

1. BACKGROUND AND INTRODUCTION

Future Navy requirements will involve deployments of underwater Remotely Operated Vehicles (ROVs) for deployment periods of between three to six months with little or no opportunity for maintenance. The ROV and its associated components must be built to achieve an operational reliability of 98% or better. The vehicle will be designed to operate from a platform with a range of 3,000 feet in any single direction. The tether will be powered, use fiber optics data transmission and must obtain the same reliability as the ROV and its subsystems.

The following operational capabilities and reliability goals for the ROV tether must be achieved for the Navy in order to meet its long-term ROV deployment goals.

A. Depth design consideration is a maximum of 6,000 feet operational depth. Consideration should also be given to a tether design which is operable to depths of 20,000 feet.

B. The tether length will be 4,000 feet in order to allow the operation of the ROV to a distance of 3,000 feet in any direction from the platform.

C. The tether must remain flexible under conditions of low temperature and long periods of inactivity in storage within the platform. The cable and jacket material will be required to retain their integrity during temperature fluctuations ranging from +110° F to +28° F and must be resistant to the effects of UV radiation, hydraulic fluids, acids, alkalies and detergents.

D. Tether construction shall include both power and fiber optic data channels for the ROV and tether design shall acheive a low self-radiated magnetic signature.

E. The tether shall be terminated at both ends via Mil-Spec connectors which will withstand long periods of immersion without delamination or loss of integrity.

F. The tether shall be designed for low drag when operated in a 5 knot current and shall have excellent abrasion resistant capabilities. Additionally, the tether shall be neutrally buoyant at its maximum deployment length.

G. The tether shall be fully water blocked to prevent wicking of water up the tether or through the connector while under pressure.

2. APPLICABLE DOCUMENTS

Operational Guidelines for Remotely Operated Vehicles, Marine Technology Society, ROV Sub-Committee, 1984.

Gibson, Philip T.; Walther, James A. Performance Characteristics of Tether Cables, pg. 37, Marine Technology Society ROV-83 Proceedings, San Diego, CA, March 1983.

3. SCOPE

The objective of this Statement of Work is to provide recommendations for the solution of long-term failure mechanisms exhibited by conventional ROV tether cables. This will be provided in the form of deliverables which will allow the ROV designer a means of selecting the most reliable means of incorporating a vehicle tether system.

The work shall focus on the development of a high reliability and highly survivable tether cable which is superior to commercially available cables. Development of the high reliability tether must address those failures which most frequently occur in commercially available cables. They involve the intrusion of water into the interstices of the cable at depth, delamination of cable connectors, abrasion and increased cable drag, degradation of the cable jacketing material and failure of internal conductors due to uneven strain distribution over the cable under high load conditions.

4. REQUIREMENTS

The contractor shall identify, from an overview, how to approach each problem identified in the Scope of this Statement of Work and in the following Design section of the Statement of Work. The major problems involving a tether assembly can be found in three major areas, tether design, manufacture and testing.

The contractor shall examine all identified design parameters and recommend a solution to these parameters which most closely matches the requirements of the tether assembly. These solutions shall be in the form of materials identification, design practices and procedures for the areas described later in this SOW. The deliverables, under this SOW, shall be in the form of a tether assembly design for a low profile, abrasion resistant tether including power cable, data cables and strength member plus connectors that is applicable for use with an ROV system. The design shall reflect the current state-of-the-art technology and assumes implementation in the next five years.

It is anticipated that the design specifications and guidelines provided as a result of this Statement of Work

shall be used to design a high performance tether assembly.

The contractor shall also provide recommendations for prototyping, but it is anticipated that prototyping will be performed by Navy engineers under their specific projects.

4.1 Tether Assembly Performance

The tether assembly described in the SOW is considered to be a lightweight component which utilizes a high strength fiber to achieve the required strength and which is neutrally buoyant when deployed. The design is complicated by the fact that it is required to be deployed in a manner that does not allow access for repair during a deployment mission, thus requiring a 98% reliability. The requirement for the cable to be low drag and to operate in currents and vehicle speeds up to 5 knots is a factor.

The management of the tether assembly by a mechanical tether management system will mean that the tether assembly will be manipulated at the platform during the deployment as a result, the tether jacketing, internal conductors and strength members will be subjected to repeated bending and stress above a level that is experienced by conventional light tether assemblies. Additionally, the tether could be subjected to the constrictive stress imposed by a physical seal required to provide for below waterline deployment. These manipulations and the forces will place a degree of stress on the overall cable assembly, which will contain fiber optic members, and the effects of both constructional stretch and elastic stretch in the strength member may have an effect upon the performance of the power and data lines within the cable.

The potential for long-term in-water or dry storage of the tether assembly (three to six months), and its exposure to both high pressure and a wide temperature range must be considered when designing the jacketing material. The memory that is present in some synthetic jacket materials at different temperature ranges can have an adverse effect upon the deployment of the tether from the management system.

The manufacture of jacketed cables has shown that without adequate machinery and manufacturing processes there exists a potential for an uneven distribution of the jacketing material over the core of the tether. This inconsistency can result in a jacket which has numerous "thin spots" which can be interpreted as potential failure points that when breached will accelerate the effects of abrasion and ultimate failure of the tether. Such jacket failures can result in water entering the interstices of the cable, uneven surface conditions which can effect the tether management and an exposure of the strength member, thereby reducing its effectiveness. A potential for these types of

failures is considered to be unacceptable.

The expected solution to the tether assembly, including connectors, will be the design of a high performance, neutrally buoyant cable of precise and repeatable dimensions. To insure that the manufacturing process remains within the guidelines, a rigorous Quality Assurance procedure will be implemented at all key points in the manufacture of the tether assembly to insure consistent and reliable performance of the tether assembly. Within the scope of the manufacturing process, new techniques may require development in order to meet the requirements of the tether assembly.

4.2 Design

A reliably performing tether assembly shall be designed which does not exhibit any of the failure modes that have been experienced in previously manufactured tethers. The design process shall address all the tether components, both individually and as an assembled unit, and shall produce a design which meets the overall ROV system reliability required.

4.2.1 Magnetic Signature

The use of platform supplied power to the ROV will produce a magnetic signature commensurate with the power levels involved. This potential signature shall be reduced or eliminated through the use of a balanced twisted power cable and shielding of all power and data wires. The balancing of all wires carrying power and data will also succeed in acting as a filter for magnetic signals originating outside of the ROV system. The contractor shall provide design guidelines in the final report (CDRL item #A003), that eliminate or reduce the magnetic signature of the ROV tether.

4.2.2 Tether Dimensions

Requirements for low drag, high relative strength and neutrally buoyant tethers represents a compromise in conflicting requirements. In the design of the tether assembly a cable of minimum diameter and high flexibility is required. The contractor shall provide design guidelines in the final report (CDRL item #A003), for a tether meeting these dimensional requirements.

4.2.3 Tether Strength Member

The material selected for the strength member of the tether should be of a light weight, high strength per volume synthetic. Elongation and elasticity of the material selected as well as the technique used to incorporate it into the tether shall be such that its constructional stretch and elastic stretch under loading do not exceed the limits of the least elastic power or data line. The contractor shall provide design guidelines in the final report (CDRL item #A003), that balance these factors to achieve the best compromise.

4.2.4 Power and Data Lines

The requirements for the conductors, which will be the ROV power and data transmission lines (as yet undefined), will dictate the gauge and type of wire to be used. In the design of the tether the requirements of the ROV will serve as the guide for the sizing of all conductors. Size of conductor to achieve reliability of operation, tether strength, elasticity and drag will be a major design factor that must be addressed. The contractor shall recommend specifications in the final report (CDRL item #A003), for conductors contained within the tether.

4.2.5 Tether Jacketing

The material used to jacket the tether is of prime concern as it will be required to remain flexible without cracking or degradation in extremes of temperature and in the presence of corrosive substances and UV radiation. The jacket material must possess an absolute minimum of memory after long-term storage within the tether management system and shall not place additional strain on either the ROV or the tether management system during deployment, i.e. it must remain flexible under all environmental conditions. The contractor shall recommend in the final report (CDRL item #A003), jacketing materials that are resistant to degradation, demonstrate little or no memory when spooled and maintain flexibility.

4.2.6 Tether Creep and Cold Flow

The jacket material shall be designed in order to retain its circular cross section while in storage. Cold flow of the jacket material or creep of the material beyond 5% concentricity will be unacceptable. Any condition which adversely affects the calculated drag of the cable or prevents the tether from being

deployed in other than a linear configuration may compromise the performance of the ROV. The contractor shall recommend design guidelines in the final report (CDRL item #A003), for jacketing material that is resistant to creep and/or cold flow.

4.2.7 Temperature Range

The tether shall be designed to operate in a wide range of temperatures from +28° F to 110° F. Under all temperature conditions expected to be encountered during deployment, the tether must remain flexible and fully operable. The tether assembly shall not degrade in static modes over a temperature range of -40° F to +140° F. The contractor shall provide tether design guidelines in the final report (CDRL item #A003), that provide for operations over the above-mentioned temperature ranges.

4.2.8 Water Blocking

The construction of the cable shall be such that the tether is fully water blocked. This is defined to mean that water is not allowed to "wick" up the inside of the tether under pressure. The use of appropriate void fillers and a high packing density can be balanced in order to achieve this condition without sacrificing flexibility. The contractor shall provide design guidelines in the final report (CDRL item #A003), for water blocking of the tether assembly.

4.2.9 Neutral Buoyancy

The tether shall be designed to be neutrally buoyant out to its maximum extension. An error, if present, shall be one of positive buoyancy not to exceed 1.0 pound per 1,000 feet. A negatively buoyant condition will be unacceptable. The contractor shall provide design guidelines in the final report (CDRL item #A003) which meet these buoyancy requirements.

4.2.10 Tether Drag

The tether should be designed to achieve minimum drag or a drag coefficient between .001 and .004. The projected ROV speed of 5 knots maximum limits the current that the vehicle can operate in, but succeeds in defining the drag forces which must be met by the tether design. Tether strum may not be a problem and the use of a fairing on the cable is unlikely due to the increase in the drag coefficient that will be seen through its use. The contractor shall provide specifications for a tether design meeting these drag requirements. The contractor shall further provide in

the final report (CDRL item #A003), predictions of cable performance in terms of drag and strumming behavior.

4.2.11 Tether Management System

A tether management system (undefined at present), will be required to control the deployment and recovery of the ROV. For some applications the tether may pass through a seal for below waterline deployments. This will involve the mechanical manipulation of the tether at all times and can result, in the extreme, of the system being required to recover a "dead vehicle". In the design of the tether, a consideration will be the "dead vehicle" condition and its effect upon the tether relative to stretch and bending over the management systems sheaves. Tether integrity must be maintained for forces two times that of the anticipated "dead vehicle" load. The contractor shall provide design guidelines, in the final report (CDRL item #A003), for the tether to maintain integrity under dead vehicle load conditions.

4.2.12 Connectors

A series of two connectors per assembly will be required. These connectors must also be capable of surviving long-term submersion without delamination or loss of integrity. The mechanical strength of the connectors shall be such that they are capable of supporting a load four times that of the highest anticipated system load without failure. Failure is defined as both mechanical failure of the connector or failure of the power and data lines. The contractor shall provide design guidelines in the final report (CDRL item #A003) for the tether to support such terminations.

4.3 Manufacturing

During the manufacturing process there exists a number of techniques which can improve the reliability of the tether assembly. The potential for techniques to exist which have not been previously applied to the manufacture of a tether cable make it desirable to explore alternatives. Non-standard options and materials should be explored and evaluated during the design and prototyping in order to create a reliable and repeatable tether assembly.

4.3.1 Jacketing Material and Technique

Cable jacketing materials such as Hytrel™ and PVC have been used frequently in the manufacture of deep ocean cables. These should act as a point of departure in the search for a material that meets the requirements of this SOW. The contractor shall investigate applicable materials, procedures and processes for assuring a well bonded, abrasion resistant and flexible jacket material and recommend, in the final report (CDRL item #A003), procedures to be used.

4.3.2 Strength Members

A variety of synthetic materials such as Kevlar™, Hytrel™, and Teknor are available on the market and can be used as strength members in a low profile neutrally buoyant tether. The contractor shall investigate all available materials suitable as strength members and recommend, in the final report (CDRL item #A003), a material for incorporation in the tether design. The contractor shall insure that the material selected is of U.S. manufacture and that it has a long-term availability.

4.3.3 Manufacturing Processes

It is well known that most manufacturers of cable in the United States often assemble components provided by other manufacturers. Frequently, the "cable manufacturers" will be provided copper conductors from one source, fiber optic materials from another source and strength members from yet another. This practice complicates the process of quality assurance. The contractor shall identify, in the final report (CDRL item #A003), all sources of process production and recommend adequate quality control procedures in order to meet the reliability required of the tether assembly.

4.4 Testing

Although testing of a prototype tether may not become the responsibility of the contractor it is, nonetheless, important that the contractor develop a testing plan to assure the reliable performance of the tether assembly. Such testing should include the evaluation of components that will be used in the manufacture of the tether and define procedures for the testing of the prototype.

Hytrel™ and Kevlar™ are trade marks of Dupont Chemical

4.4.1 Test Samples

A testing procedure shall be recommended by the contractor to insure that all component units and assemblies can be shown to perform in accordance with the requirements of the tether assembly. Such tests should demonstrate both material suitability as well as process reliability and can be included in the production of a full assembly. The contractor shall provide, in the final report (CDRL item #A003), testing procedures for component assembly and full assembly production.

4.4.2 Representative Test Samples

The contractor shall provide recommendations for making test samples of the tether after production in the final report (CDRL item #A003). Such samples shall be representative of the overall product.

4.4.3 Testing Under Pressure and Temperature

A critical component of the tether design will be its performance under extremes of temperature and pressure. It can be anticipated that low temperature/high pressure conditions will exist in the field. The contractor should recommend testing procedures, both short and long term, which will prove the neutral buoyancy, watertight integrity and overall flexibility of the tether assembly. Additionally, tests to demonstrate the integrity of the tether under all loading conditions should be recommended. The contractor shall recommend, in the final report (CDRL item #A003), testing procedures that adequately demonstrate tether performance under all conditions expected to be encountered.

4.4.4 Other Potential Design Problems

There may be potential problems encountered in high performance tether design other than the problems listed above. The contractor shall detail any other problems of concern to a design engineer and provide potential solutions for these problems in the final report (CDRL item #A003)

4.4.5 Prototyping

In order to demonstrate the suitability of a tether assembly design, it is desirable to prototype the design and test its performance. The contractor shall provide recommendations, in the final report (CDRL item #A003), for prototyping tether assembly designs.

5. DELIVERABLES

The deliverables on this project shall be in contractor format and in accordance with the attached Contract Data Requirements List (CDRL), Form DD1423. The details of the required deliverables are as follows:

5.1 Program Plan (A001)

The contractor shall develop a program plan in accordance with CDRL #A001 identifying how to approach each problem technically (including breakpoints), alternative approaches, and a schedule for each required deliverable in Section 4 of the SOW. The plan shall elaborate on the contractor's proposed technical approach to the SOW and detail how the contractor will perform each required item within the allocated time and cost. A draft program plan shall be delivered 30 days after contract award, and is subject to Government approval. A final version of the program plan, with Government comments incorporated, shall be required 15 days after the contractor's receipt of the Government's comments.

5.2 Status Reports (A002)

The contractor shall provide project status in accordance with CDRL item #A002 by the fifteenth of each month for the previous calendar month.

5.3 Final Report (A003)

A draft final report prepared in accordance with CDRL item #A003, describing all research results and conclusions, shall be submitted 60 days prior to completion of the contract for review and comment.

A final report updating the draft report, as required by the review comments, shall be submitted 30 days after the contractor's receipt of the Government's comments on the draft report.

Specific deliverables to be included in the final report are the following:

5.3.1 Problem Documentation

Section 4 requires the contractor to provide evaluations, specifications, design guidelines, comparisons, descriptions and/or recommendations for each specific problem and to include the results as separate, identifiable items in the final report. The

results shall be prepared in accordance with CDRL item #A003 for the ROV tether assemblies tasking as directed in items 4.2.1 through 4.4.4 inclusive. The specific items to be reported are:

(4.2.1) Magnetic Signature

The contractor shall provide design guidelines that eliminate or reduce the magnetic signature of the ROV tether.

(4.2.2) Tether Dimensions

The contractor shall provide design guidelines for a tether meeting the dimensions required to achieve high reliability in the parameters identified.

(4.2.3) Tether Strength Member

The contractor shall provide design guidelines that balance these characteristics to achieve the optimum design.

(4.2.4) Power and Data Lines

The contractor shall recommend specifications for conductors contained within the tether.

(4.2.5) Tether Jacketing

The contractor shall recommend jacketing materials that are resistant to degradation, demonstrate little or no memory when spooled and maintain flexibility.

(4.2.6) Tether Creep and Cold Flow

The contractor shall recommend design guidelines for jacketing materials that are resistant to creep and/or cold flow.

(4.2.7) Temperature Range

The contractor shall provide tether design guidelines that provide for operations over the above-mentioned temperature ranges.

(4.2.8) Water Blocking

The contractor shall provide design guidelines for water blocking of the tether assembly.

(4.2.9) Neutral Buoyancy

The contractor shall provide design guidelines which meet the buoyancy requirements os Section 4.2.9.

(4.2.10) Tether Drag

The contractor shall provide specifications for tether design meeting the drag requirements of Section 4.2.10. The contractor shall further provide predictions of cable performance in terms of drag and strumming behavior.

(4.2.11) Tether Management System

The contractor shall provide design guidelines for the tether to maintain integrity under dead vehicle load conditions.

(4.2.12) Connectors

The contractor shall provide design guidelines for the tether to support the terminations identified in Section 4.2.12.

(4.3.1) Jacketing Material and Technique

The contractor shall investigate applicable materials, procedures and processes for assuring a well bonded, abrasion resistant and flexible jacket material and recommend manufacturing procedures to be used.

(4.3.2) Strength Members

The contractor shall insure that the material selected is of U.S. manufacture and that it has a long-term availability.

(4.3.3) Manufacturing Processes

The contractor shall identify and evaluate all sources of process production and recommend adequate quality control procedures in order to meet the reliability required of the tether assembly.

(4.4.1) Test Samples

The contractor shall recommend testing procedures that adequately demonstrate tether performance under all conditions expected to be encountered.

(4.4.2) Representative Test Samples

The contractor shall provide recommendations for making test samples of the tether after production.

(4.4.3) Testing Under Pressure and Temperature

The contractor shall recommend testing procedures that adequately demonstrate tether performance under all conditions expected to be encountered.

(4.4.4) Other Potential Design Problems

The contractor shall detail and provide detailed potential solutions for these problems in the final report.

(4.4.5) Prototyping

The contractor shall provide recommendations for prototyping tether assembly designs.

STATEMENT OF WORK

FOR

High Reliability Autonomous Underwater Vehicle (AUV)

Variable Ballast Systems

Prepared By:

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Prepared For:

Office of Naval Research (ONR)
Warfare Technologies Division
(ONR Code 122)

TABLE OF CONTENTS

Section/Paragraph

STATEMENT OF WORK

1. BACKGROUND AND INTRODUCTION

Future Navy requirements will involve protracted deployments of underwater Remotely Operated Vehicles (ROVs) and Autonomous Untethered Vehicles (AUVs). To date, the performance of ROVs has been heavily dependent on the quality and quantity of the maintenance and support available during relatively limited deployments. An ROV design that is appropriate for industrial (e.g., petroleum industry) operations, with limited exposure and the expectation of much maintenance, as a tradeoff against higher initial cost, is inappropriate for military missions with little or no opportunity for upkeep. As a result, the common practice of modifying existing ROVs and ROV subsystems for long term, at-sea storage and/or operation without maintenance is undesirable and is not considered to be a long-term solution for extended mission Navy operations.

The Statement of Work (SOW) for a high reliability Variable Ballast System will be limited to Autonomous Underwater Vehicles (AUVs) in order that the impact of limited power on the performance of the variable ballast system may be fully explored.

The following operational capabilities and reliability goals need to be achieved for the Navy to meet its long term deployment AUV requirements. The AUV's must be designed and built to achieve an operational reliability of 98% or better when operating from submarines during protracted deployments (3-6 months wet or in a powered-down configuration for one to two months followed by several weeks of subsequent operations). The AUV system's operational capabilities to be considered are as follows:

1. The operational depth design consideration is a maximum of 3,000 ft. Consideration shall also be given to systems that have a maximum depth capability of 20,000 ft.

2. The system shall not have a tether.

3. The AUV system shall have low self-radiated noise, according to the goals shown in Figure I, and its auxiliary acoustic components shall not interfere with the platform sensors. The entire system shall minimize acoustic radiation. Noise limitation shall receive the same priority as reliability in design.

4. The AUV system's magnetic field shall not interfere with the platform or its sensors and vice versa.

5. The AUV's capacity for a variety of work tasks, including moderate duty work and moderate power manipulators, shall also be considered.

6. The AUV's maximum nominal speed shall be 5 knots.

All aspects of the system life cycle that may offset reliability were considered in an initial investigation, including design, procurement practices, fabrication, inspection, in-service use and maintenance. The reliability problems identified in the investigation report covered the entire development phases of design, manufacturing and in-service life. The in-service life phase, concerned with training, maintenance and documentation are not to be considered under the tasking of this SOW, but later on as part of a specific system design. The focus of this SOW is on the application of technology to improve reliability.

Specifically, this statement of work addresses AUV variable ballast system reliability problems and how their design might be improved to help obtain the long range Navy objective of achieving a substantial increase in the extended mission reliability of AUVs.

2. SCOPE

The objective of this SOW is to provide recommendations for specific design solutions to the problem of remotely ballasting AUV systems. This will be presented in the form of deliverables so that designers can use this information in the creation of new vehicles and systems, or in troubleshooting/retrofitting existing systems.

A high reliability, long term deployment AUV is expected to encounter two scenarios that will require a variable ballast system.

1. One would require a modest degree of ballast flexibility (0-450 lbs. for trimming) for a vehicle operating over a range of depths, temperatures, and salinity conditions. Included within this category will be compensation for small amounts of air trapped in ROV/AUV components (i.e. pressure compensated oil filled connectors (PCOF) and cable assemblies, and oil compensated electric windings) as that air compresses or dissolves with depth.

2. The second involves payload compensation which deals with larger volumes and higher flow rates. Payload compensation could include deposit/recover of objects weighing approximately 2500 lbs. Two time periods for payload compensation shall be considered: compensation within 1/2 hour and compensation within 24 hours, respectively.

There are two common methods of changing a underwater vehicle's buoyancy during deployment. Both require pumping systems. The first involves the system pumping an amount of water inboard or outboard with the use of fixed size ballast tanks. In this manner the system varies its weight while maintaining a constant displacement. The second involves the system displacing less or more by pumping a stored supply of a low density fluid into a variable size bladder or cylinder/piston assembly thereby varying its displacement while maintaining a constant weight. For both methods the amount of buoyancy changed per unit volume of fluid pumped is similar. In fact, the two methods are nearly identical, differing only in what is considered to be the boundary of the vehicle and fluid pumped.

However, to meet AUV system noise signature goals, a Variable Boyancy (VB) system may have to consider quieter alternatives (i.e. change of ballast over a longer period of time, or taking on/expelling sea water via seepage through a porous plug.

An important part of this SOW is to provide an analysis of existing VB systems, outlining the tradeoffs between the different types and indicating which type would allow the greatest potential for future modification while supplying high reliability on long term deployments. These VB systems shall have weight displacement capabilities of 450 lbs. and 2,500 lbs. each for the two depth regimes at 3,000 and 20,000 ft. Should a VB system of the weight displacement capabilities not be available for these two regimes, the contractor shall conduct a cursory design effort to facilitate the component comparison/reliability recommendations. This cursory design effort should not exceed two man weeks of effort for any of the four weight/depth combinations not covered in the analysis of existing VB systems. Any cursory design effort shall provide a forward and aft ballast tank and provision for transfer of fluid between the two.

The work will be focused on ways to improve the reliability of VB systems and associated hardware, including pumps, tanks and plumbing while meeting the AUV noise signature goals of Figure I. Trade off studies conducted to satisfy the twin priorities of reliability and quietness should include analysis of the relationships between noise and flow rates/velocities through pipes, flow limiters, valves, pumps, etc. For schemes using an intermediate fluid to avoid running high pressure pumps, more volume is required; consequently, the study should address volumetric efficiency. Also, the deliverables for this SOW should include design recommendations that would allow for the ballasting system to be upgraded at a later date to be either oil or salt water based.

3. REQUIREMENTS

The contractor's proposal shall identify how to approach each problem technically, alternative approaches, costs and schedules. The approach shall address all the problems as delineated above in Section 2 and as follows.

The contractor shall examine all the reasonable methods for designing a VB system for an AUV and recommend design and/or procedural solutions to foreseen problems so they can be implemented at a later date for testing and/or evaluation purposes. These solutions will be in the form of deliverables described later in this section of the SOW. The deliverables shall reflect the current state-of-the-art technology, and assume implementation in the next five years.

3.1. Variable Ballast Design Evaluation

There are a number of VB systems currently in operation on manned submersibles and others in design phases by major Navy contractors for ROVs/AUVs. The contractor shall review these designs and group them in a list via design/capability breakpoints (i.e. weight displaced, depth capability, etc.). This list will be used to identify those designs which offer the greatest promise for, and the least modifications for, meeting high reliability requirements. From this list, the contractor will select the most promising designs that represent 450 lbs. and 2,500 lbs. weight displacement capabilities each for two depth regimes, 3,000 ft and 20,000 ft. The contractor shall identify any components other than those listed in section 3.2 that are categorized as those having low reliability. The contractor shall then perform tradeoffs and generate design specifications for these components, and provide the lists and results as an attachment to the final report (CDRL item #A003). Should variable ballast systems not be available for any of these four combinations, the contractor shall conduct a cursory design effort, not to exceed two man weeks each, to facilitate the component comparison/reliability recommendations. The results of this design effort shall be provided in the final report (CDRL item #A003).

3.2. Critical Design Areas

The overall objective is to develop a reliable longer-term deployment of AUVs than is possible with current commercial vehicle designs modified to meet Navy requirements. Several specific critical areas have been identified which must be addressed in order to improve reliability to an acceptable level. In dealing with specific design recommendations for maximizing system reliability, the contractor must keep in mind that these must be based on the realization that compromise is an inevitable part of every design effort.

Consequently, the importance of each recommendation, relative to other recommendations, must be indicated. Further, the contractor shall provide reasonable comparison information on the application of less than optimum alternatives and their possible consequences.

The designs for the VB systems shall include capabilities for displacing up to a maximum of the two weights required, 450 lbs. and 2,500 lbs. Two system designs shall be considered, each capable of operating at the two depthratings specified, 3,000 ft. and 20,000 ft.

Specific considerations that should be kept in mind include the fact that the AUV to use the VB system is designed to have a low noise signature and the variable ballast system design should not significantly contribute to the overall acoustic signature of the ROV. Acoustic signature goals for the AUV system are presented in Figure I.

3.2.1 Variable Ballast Pumps

The heart of VB systems is usually a pump which transfers fluid in and out of "hard" ballast tanks or displacement receptacles. These pumps are required to pump against high pressures. For a number of existing VB systems, exotic special purpose pumps have been designed. It is felt that there may be a number of standard pumps in existence that would require only minor modifications in order to be applied to high reliability VB systems for use at the intended depths. The designed system may be powered by hydraulics or an electrical system. The pump does not have to be a rotary type and may be of a staged type. For this component, simplicity and reliability need to be emphasized. The contractor shall provide descriptions of VB pumps in use today indicating tradeoffs. Also, the contractor shall provide design and recommendations for a variable ballast pump system which provides the greatest opportunity for updating in the future, and provide the results in the final report (CDRL item #A003).

3.2.2 System Plumbing

Considerations shall be given to the physical size and configuration of the line runs and fixtures in the VB system. ROV/AUV designs are typically compact. This restriction requires that subsystems shall not be overly bulky and consume more space than is necessary while maintaining high reliability. The contractor shall provide recommendations and/or designs for optimal physical layout for variable ballast plumbing systems assuming forward and aft ballast tanks and provision for transfer of fluid (i.e. water or other)

between the two. Results shall be provided in the final report (CDRL item #A003).

3.2.3 Control Valving

As indicated in section 3.2.1, the pumps involved in the VB system are often required to pump against high pressures. Initial startup can cause stalling in hydraulic systems and excessive currents in electrical systems. The system design shall consider the startup forces and include, if appropriate, a method of unloading the pump prior to startup if necessary. The contractor shall provide recommendations for the use of control valving to eliminate undo startup forces. In any variable ballast system, control valves, relief valves and flow direction control valves play a crucial part in the reliability of the system. In some designs the system is allowed to free flow in one direction. This valving is also important in controlling free flow. The contractor shall evaluate and recommend design and placement of all valving in order to maintain high reliability and quietness, and provide the results in the final report (CDRL item #A003).

3.2.4 Corrosion

Certain components of any variable ballast system can become exposed to a corrosive environment. This is particularly true where sea water comes into contact with high partial pressures of oxygen inside pressurized "hard" ballast tanks. Further, in some undersea environments such as deep sea vents, highly corrosive compounds can be encountered that may be detrimental to system components. Considerations should be given to the selection of suitable materials in the system for components that would contain pressurized air and seawater. The contractor shall provide recommendations and tradeoffs for suitable materials for hard ballast tank systems and other VB system components to prevent or resist corrosion, and provide the results in the final report (CDRL item #A003).

3.2.5 Fluid Pumped

In a displacement VB system, a fluid such as oil is typically pumped in and out of an expanding receptacle to alter the vehicles displacement. The fluid that is pumped shall be selected carefully to be the right viscosity and lack corrosive components that may damage internal system parts. Also, it shall be a fluid that is resistant to changes in viscosity with changes in temperature and pressure. In order to maintain high reliability, the fluid may also be required to act as a lubricant to other components of the VB system. The

contractor shall evaluate and recommend appropriate fluids to be used in any recommended systems which pump fluids other than seawater. The contractor shall provide the results in the final report (CDRL item #A003).

3.2.6 Displacement Receptacle

A variable displacement system often utilizes an expanding module such as a bellows to pump fluid to and from, thereby changing the overall displacement of the system. A high reliability AUV may require a VB system having reliable displacement receptacles. The contractor shall provide recommendations and/or designs that include those for a receptacle such as a metal piston and cylinder or other ruggedized design. The contractor shall provide the results in the final report (CDRL item #A003).

3.2.7 Pressurized Ballast Tanks

In VB systems, particularly those used in deep water, it may be advantageous and increase reliability to use gas pressurized hard ballast tanks. The contractor shall evaluate the impact on the reliability of the VB system using pressurized gas systems having forward and aft tanks and provision for transfer of fluid between the two. Results shall be provided in the final report (CDRL item #A003).

3.2.8 Efficiency

Efficiency, capacity and speed are crucial performance specifications for VB systems. This system shall be expected to displace totals of 450 lbs. and 2,500 lbs. in time periods ranging from 1/2 hour to 24 hours. The contractor shall provide evaluations/tradeoffs and recommendations for these and other rates of achieving this ballast change. The contractor shall also provide evaluations of different methods of achieving these specifications while maintaining high reliability, and provide the results in the final report (CDRL item #A003).

3.2.9 Sensors

In order to achieve overall system reliability and quietness, variable ballast designs shall include sensors to provide information on trim, buoyancy, fluid levels and pump performance. The contractor shall evaluate high reliability sensors to provide this information and provide the results in the final report (CDRL item #A003).

3.2.10 Radiated Noise Levels

Since the AUV shall have low self-radiated noise, in accordance with the goals of Figure I, the VB system shall be designed to provide high reliability and perform without radiating excessive noise. The contractor shall provide recommendations and/or designs which minimize radiated noise, and provide the results in the final report (CDRL item #A003).

3.3 Manufacturing Errors

During the contract the contractor shall develop a list of common manufacturing errors found that may cause unreliability in subsea VB systems. This list will be valuable in warning the AUV designer or manufacturer of their existence. The contractor shall make this list available as an attachment to the final report (CDRL item #A003). The list of errors shall include explanations, desirable alternative solutions, and recommendations.

3.4 Reference Documentation

The contractor shall make a thorough survey of applicable military standards, specifications and handbooks. The contractor shall compile all such documents, cross-referenced and explained so that the designer will have a single, concise source for selection of applicable controlling documents to reference during the preparation of material, process, or product specifications. The contractor shall draw on these and other sources of information, and on his own experience in the design and implementation of underwater VB systems of all types, and produce a compendium of specific guidelines on how to design to prevent problems (historical and expected) which plague VB systems reliability. This compendium shall be presented as an attachment (CDRL item #A003) to the final report.

4. DELIVERABLES

Design evaluations for the technical aspects of the VB system which contribute to failures shall be a prime product (CDRL item #A003). The contractor shall provide a list of common manufacturing errors found to cause variable ballast failures. Other deliverables required are a program plan (CDRL item #A001), status reports (CDRL item #A002) and a final report (CDRL item #A003).

The deliverables on this project shall be in contractor format and in accordance with the attached Contract Data Requirements List (CDRL), Form DD1423. The details of the required deliverables are as follows:

4.1 Program Plan (A001)

The contractor shall develop a program plan in accordance with CDRL #A001 identifying: how to approach each problem technically (including breakpoints), alternative approaches, and a schedule for each required deliverable in Section 3 of the SOW. The plan shall elaborate on the contractor's proposed technical approach to the SOW and detail how the contractor will perform each required item within the allocated time and cost. A draft program plan shall be delivered 30 days after contract award, and is subject to Government approval. A final version of the program plan, with Government comments incorporated, shall be required 15 days after the contractor's receipt of the Government's comments.

4.2 Project Status (A002)

The contractor shall provide project status in accordance with CDRL item #A002 by the fifteenth of each month for the previous calendar month.

4.3 Final Report (A003)

A draft final report prepared in accordance with CDRL item #A003, describing all research results and conclusions, shall be submitted 60 days prior to completion of the contract for review and comment.

A final report updating the draft report, as required by the review comments, shall be submitted 30 days after the contractors receipt of the Governments comments on the draft report.

Specific deliverables to be included in the final report are the following:

4.3.1 Variable Ballast Design Evaluation

The contractor shall provide full descriptions of existing designs of VB systems, indicating tradeoffs and recommendations. The contractor shall provide lists and evaluations of existing variable ballast systems and identify components other than those listed in section 3.2 having low reliability. The contractor shall also generate design specifications for these components. If VB systems are not available for these depth regimes, the contractor shall provide a cursory design effort to support the component comparison/reliability recommendations for the four weight/depth combinations previously cited. (Item 3.1 Variable Ballast Design Evaluation.)

4.3.2 Problem Documentation

Section 3 requires the contractor to provide evaluations, specifications, comparisons, tradeoffs, descriptions, and/or recommendations for each specific problem and to include the results as separate, identifiable items in the final report. The results shall be prepared in accordance with CDRL item #A003 for the AUV VB system components, subsystems, supporting/auxiliary equipment or processes as directed in items 3.2.1 through 3.2.10 inclusive. The specific items to be reported are:

(3.2.1) Variable Ballast Pumps

The contractor shall provide recommendations for pump designs and/or pumps available that can be expected to perform quietly in a high reliability system.

(3.2.2) System Plumbing

The contractor shall provide recommendations and/or designs for a VB system physical layout that can be readily modified at a later date. The contractor shall indicate tradeoffs in various physical configurations of VB systems.

(3.2.3) Control Valving

The contractor shall provide recommendations and/or designs for the use of valves or other methods to prevent pressures from stalling or otherwise causing detriment to the system during initial startup.

(3.2.4) Corrosion

The contractor shall provide recommendations and/or designs that will prevent excessive corrosion to the VB system components that may be exposed to severe corrosion environments.

(3.2.5) Fluid Pumped

For designs that use a variable displacement method for changing buoyancy, the contractor shall evaluate various fluids appropriate for a high reliability, low noise AUV system.

(3.2.6) Displacement Receptacle

As in 3.2.5 (above) for designs that use a variable displacement method, the contractor shall provide recommendations and/or designs for a fluid

receptacle that will perform adequately on a high reliability system.

(3.2.7) Pressurized Ballast Tanks

The contractor shall provide evaluations and recommendations for the use of pressurized ballast tanks in variable ballast systems for each of the working depths described.

(3.2.8) Efficiency

The contractor shall provide design recommendations and tradeoffs based on size vice efficiency in VB systems. The contractor shall also provide tradeoffs and recommendations for various rates of achieving 0-450 lbs. and 0-2,500 lbs. changes in ballast.

(3.2.9) Sensors

A number of sensors may be required in a VB system in order to maintain high reliability. The contractor shall provide evaluations of high reliability performance indicating sensors that can be integrated into a VB system for AUVs.

(3.2.10) Radiated Noise Levels

The contractor shall provide design recommendations and tradeoffs to minimize acoustic output of the VB systems for AUVs to the specifications outlined in Figure I.

4.3.3 Manufacturing Errors

The contractor shall provide a list of common ROV/AUV subsea VB system manufacturing errors including desirable alternative solutions and explanations. (Item 3.3 Manufacturing Errors.)

4.3.4 Reference Documentation

The contractor shall provide a compendium of specific guidelines on how to design to prevent problems which may be encountered in AUV VB system's reliability.

The contractor shall make a thorough survey of applicable military standards, specifications and handbooks. He shall compile all such documents, cross-referenced and explained so that the designer will have a single, concise source for selection of applicable controlling documents to reference during the preparation of material, process, o. product specifications. (Item 3.4 Reference Documentation.)

APPENDIX B

EXPERT DATABASE

APPENDIX B
EXPERT DATABASE

Sandi L.M.	Agen	Honeywell	San Diego	CA
Carl S.	Albro	Battelle BDD	Duxbury	MA
C.M.	Alexander	UCSD, SIO	La Jolla	CA
Larry	Armbrewster	Honeywell	Seattle	WA
Russell	Arnold	NCEL	Port Hueneme	CA
Theodore	Austin	NUWES	Keyport	WA
James	Bailey	Crouse Hinds Elec.	La Grange	NC
Richard	Berey	Nat'l Undersea Research	St. Croix	VI
Alan	Berian	Rochester Corporation	Culpeper	VA
Henri	Berteaux	W.H.O.I.	Woods Hole	MA
Al	Bertoldo	Advanced Cable	Laguna Hills	CA
Richard	Bloomquist	NSRDC	Annapolis	MD
Paul	Boehm	Battelle BDD	Duxbury	MA
Bruce	Boston	Honeywell	San Diego	CA
Alan V.	Bray	Texas Research Institute, Inc.	Austin	TX
Gary	Brown	Consolidated Cable	Idylwild	CA
Wayne J.	Bywater	Nortech	Troy	NY
Robert	Chome	NSRDC	Annapolis	MD
Andrew	Clark	Harbor Branch Foundation	Fort Pierce	FL
Peter	Clay	Bouy Group	Woods Hole	MA
Duane	Clayton	Rochester Cable	Culpeper	VA
Kenneth	Collins	Applied Remote Tech	Scripps Ranch	CA
David	Cook	Flotation Technology	Biddeford	ME
Mike	Cook	NOSC	San Diego	CA
Roger	Cook	Harbor Branch Foundation	Fort Pierce	FL
Thomas	Coughlin	Vector Cable	Sugarland	TX
Joseph	Craven	SUBDEVGRU-1, DSV-4	San Diego	CA
James	Cummings	Honeywell	San Diego	CA
Roy	Dody	NOSC	San Diego	CA
James	Dombrowski	NOSC	San Diego	CA
Philip	Doringer	D.G. O'Brien	Seabrook	NH
Alan	Driscoll	URI	Narragansett	RI
Dave	Dunfey	D.G. O'Brien	Seabrook	NH
Norman	Estabrook	NOSC	San Diego	CA
Marshall	Flake	Harbor Branch Foundation	Fort Pierce	FL
Hugh L.	Frisbie	Honeywell	San Diego	CA
David	Fuller	Spears Associates	Norwood	MA
Thomas	Garriety	SUBDEVGRU-1 ,UVD	San Diego	CA
Robert A.	Gatherer	SUBDEVGRU-1 ,UVD	San Diego	CA
Philip	Gibson	Tension Mmbr. Tech	Westminster	CA
Jack	Graham	Maloney	Houston	TX
Bruce	Griffin	NAVSEA	Washington	DC
Thomas	Gurney	Martin Marietta	Orlando	FL
Robert	Gwalchmai	Naval EODTC	Indian Head	MD
Kevin	Hardy	UCSD, SIO	La Jolla	CA
John	Hart	APL Univ of Wash.	Seattle	WA
Bruce	Harting	Kintec	St. Peterburg	FL
Robert	Hawkins	Naval EODTC	Indian Head	MD
William	Hayes	Martin Marietta	Oakwood	TN

James	Held	NOSC	San Diego	CA
Patrick	Hickey	DSL, W.H.O.I.	Woods Hole	MA
Harry	Hilberg	D.G. O'Brien	Seabrook	NH
Terry	Hoffman	NUSC		HI
Bruce	Hood	NSRDC	Annapolis	MD
Dennis	Hurst	Honeywell	San Diego	CA
Pamela J.	Hurst	Honeywell	San Diego	CA
Jack	Jaeger	Saches Engineering	San Diego	CA
Daniel	Johnson	Ketema A & E	El Cajon	CA
Vicky	Johnson	NCEL	Port Hueneme	CA
Christopher	Kennedy	SUBDEVGRU-1, DSV-3	San Diego	CA
Roy	Knapp	Univ. of Hawaii	Honolulu	HI
Ted	Kretchner	NCEL	Port Hueneme	CA
Pat	Larkin	ISE	Vancouver	BC
Richard	Longabaugh	Impulse CTRS	San Diego	CA
Richard	Laudermilk	Seacon	El Cajon	CA
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APPENDIX C

TECHNICAL REVIEW BOARD (TRB) PERSONNEL

APPENDIX C

TECHNICAL REVIEW BOARD (TRB)

The contractor would like to acknowledge the assistance of the following Technical Review Board (TRB) Personnel who participated in finalizing the seven technical Statements of Work included in this report.

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APPENDIX D

BIBLIOGRAPHY

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BIBLIOGRAPHY

Gibson, P.T. Operational Characteristics of Electromechanical Cables. New Orleans, LA: Third International Offshore Mechanics and Arctic Engineering Symposium [February 12-17, 1984].

Hobaica, E.C. and Cook, S.D., "The Characteristics of Syntactic Foams Used for Buoyancy". Journal of Cellular Plastics [April 1968].

Jackson, Doug and Clay, Peter. "Syntactic Foam Sphere Improves Oceanographic Mooring Performance". Sea Technology Magazine [September 1983].

Jenkins, J.F. Inspection of Objects Retrieved from the Deep Ocean - AUTEC Acoustic Array. Port Hueneme, CA: Civil Engineering Laboratory, Technical Report N-1424 [1976].

McCartney, J.F. and Wilson, J.V. High-Power Electromechanical Cable Connectors for Deep Ocean Applications. Port Hueneme, CA: Civil Engineering Lab., Naval Construction Battalion Center, Technical Report R806 [April 1974].

O'Brien, Donald G. An Update on Recommended Techniques for Terminating Underwater Electrical Connectors to Cables. Marine Technology Society Tenth Annual Conference Proceedings [1967].

O'Brien, Donald G. Application of Glass-Hermetic-Sealed Watertight Electrical Connectors. San Diego, CA: Marine Technology Society [June 1967].

Product Engineering. "Designer Profile - Working with materials, this engineering looks to the sea", [September 22, 1969].

Reinhard, Donald L., and Smith, Stewart W. Macrosphere Development Provides Cost Effective Buoyancy Packages for ROV'S, Agawam, MA: Albany International Corporation.

Sandwith, C.J. "O-Ring Installation for Underwater Components and Applications". Naval Research Laboratory Memorandum Report 4809 [April 15, 1982].

Shutov, F.A. Syntactic Polymer Foams. Moscow 125820, USSR: Mendeleev Institute of Chemistry and Technology, Dept. of Polymer Processing [1985].

"Specification for Sea Cliff Modification Syntactic Foam," N00024-80-B-7102 [October 1979].

Stachiw, J.D. Graphite Fiber-Reinforced Plastic Pressure Hull Mod 1 for the Advanced Unmanned Search System (AUSS). San Diego, CA: Naval Ocean Systems Center, Technical Report No. 1182 [December 1986].

Stachiw, J.D. Pressure Resistant Ceramic Housings for Deep Submergence Systems. San Diego, CA: Naval Ocean Systems Center, Technical Document 1294 [June 1988].

Stachiw, J.D. Deep Submergence AUSS Pressure Hull Project, San Diego, CA: Naval Ocean Systems Center, Technical Document "Thick Composites in Compression" [July 1988].

Stachiw, J.D. and Frame, B. Graphite-Fiber-Reinforced Plastic Pressure Hull Mod 2 for the Advanced Unmanned Search System Vehicle. San Diego, CA: Naval Ocean Systems Center, Technical Report 1245 [August 1988].

Stachiw, J.D. and Held, J.L. Exploratory Evaluation of Alumina Ceramic Cylindrical Housings for Deep Submergence Service: The Second Generation NOSC Ceramic Housings. San Diego, CA: Naval Ocean Systems Center, Technical Report 1176 [September 1987].

"Syntactic Buoyancy Material for High Hydrostatic Pressures", Military Specification MIL-S-24154A (SHIPS) [March 28, 1967].

Watkins, L.W. Predicting the Long-Term Performance of Syntactic Foam Buoyancy in Production Riser Systems. Canton, MA: Grace Emerson & Cuming [May 1986].

Wilson, J.V. Coaxial Underwater Mateable Connectors - A New Technology for Seafloor Structure Applications. Port Huenemo, CA: Technical Report R875, Civil Engineering Laboratory, Naval Construction Battalion Center [September 1979].

APPENDIX E

DISTRIBUTION

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DISTRIBUTION

ENCLOSURE NUMBER 1
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INSTRUCTIONS FOR DISTRIBUTION

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